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Differential Omega System Development and Evaluation

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August 1981

Final Report

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16. Abstract
This report describes a development and evaluation program for Differential Omega in general aviation. The program was a cooperative venture between the FAA and Transport Canada. SCT performed system design, program management, and flight test on behalf of the FAA. Tracor, Inc. provided modified Omega airborne receivers under subcontract to SCT. Flight tests took place in Alaska aboard a Convair 580 provided by the FAA. Monitor stations were located in Anchorage and at Deadhorse. The most definitive results were obtained from flight tests conducted in October 1980 and February 1981. Important results included: (a) data-link range varied from 44 nm to 198 nm, (b) random component of navigation error was 0.25 nm, 2-D RMS, (c) range decorrelation error was about 2 nm over a distance of 550 nm, (d) transient response of the system-following aircraft procedure turns was characterized by a positional overshoot of about 1.5 nm, followed by a monotonically decreasing error with a two-minute time constant. Recommendations are made for improving system performance.

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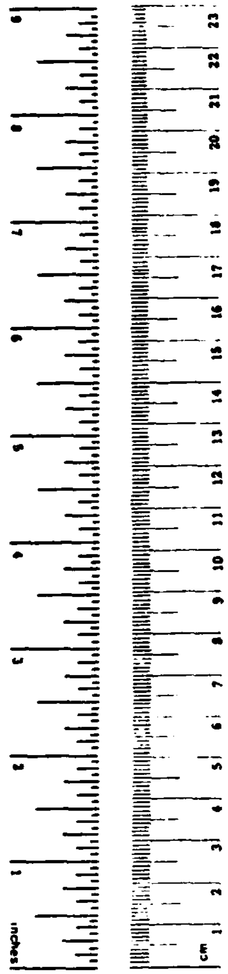
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

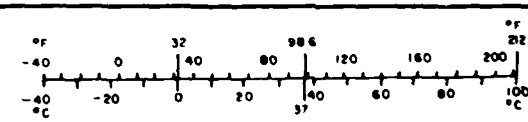
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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The success of this project is a result of cooperative efforts by several organizations and many individuals. Significant contributions have been rendered by Frank Adams and Wayne McKay of Transport Canada; George Quinn and Bob Erikson of the FAA; Bill Donnell, Bob Caddel, Bill Quinlivan and Dr. Obie Baltzer of Tracor; and Rich Vargus, Georgina Bailie, Karen Lockman, and Clare Walker of Systems Control, Inc. Special thanks for their splendid support are due to FAA personnel in Alaska, including Tom Wardleigh and the aircraft pilots, Roy Pebsworth and the avionics technicians, and Bruce Benson and the technicians at Merrill Field and Deadhorse. The enthusiastic support of these individuals and many others we have not named is deeply appreciated.

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I. INTRODUCTION

1.1 GENERAL

This is a final report on Task V of FAA Contract DOT FA75WA-3662, Differential Omega System Development and Evaluation. The Task V effort began 27 August 1977 and was completed on 15 August 1981. The overall plan for this project contemplated a cooperative approach involving System Control, Inc. (SCI), the FAA Alaska region, the Canadian Ministry of Transport [Transport Canada] and Tracor, Inc. [Tracor], where Tracor was involved via subcontract to SCI.

1.2 OBJECTIVES

The overall objective of this project has always been to demonstrate Differential Omega as a possible alternative to VOR/DME within an operational environment that includes enroute and terminal area operations. The area of North Alaska and Northwest Canada was selected as the location for the demonstration. Basic Omega coverage over this area is excellent, but there is a sparsity of more precise navigational aids.

To achieve the project objective, early planning called for three ground stations to be implemented and up to six airborne units were to be employed. The ground stations were planned at the following sites:

- Fairbanks, Alaska
- Deadhorse, Alaska
- Inuvik, Canada

At each ground station, the existing aeronautical beacon transmitter was to be modified to transmit the Differential Omega data. The direction finding capabilities of the beacons were not to be affected. The aircraft equipped with the airborne units were to conduct normal operational flights within the coverage area for up to one year. Data were to be acquired both automatically and manually.

The data of interest were to be such as needed to assess the effective range and accuracy of Differential Omega. In addition, operational type data were to be acquired to the extent possible.

It was intended originally that the results of this field test demonstration were to lead to a complete description of a Differential Omega system description including:

- Ground Stations
- Avionics Equipment
- Data Formats
- Interfaces
- Operating Modes

and a statement of the performance achieved in an operational environment.

During the course of Task V some of the intermediate objectives changed, although the ultimate objective remained unchanged. Some of the more important modifications in the project have been as follows:

- Ground stations have been established at Anchorage, Alaska, and Deadhorse, Alaska. No ground station has been established in Northwest Canada although a ground station has been set up temporarily in a Transport Canada laboratory in Ottawa, Ontario.

- Two sets of Differential Omega avionics have been developed to operational status and a third set has been partially developed. One operational set has been installed and routinely flight tested in an FAA aircraft in Anchorage. The second operational set has been tested by Transport Canada in Ottawa.

- All FAA-sponsored flight tests under this project have been conducted in Alaska. No flight tests have taken place in Northwest Canada. Some mobile tests of the second operational set have been conducted via test van near Ottawa.
- During the October 1980 flight tests, Tracor conducted an experiment designed to provide cancellation of precipitation-static interference in airborne Omega applications. The experiment was performed under the subcontract from SCI to Tracor.
- The project was completed on August 15, 1981.

1.3 BACKGROUND

Omega, a VLF navigation system based on a worldwide network of eight transmitters operated at 10.2, 11.05, 11.333 and 13.6 kHz, provides global coverage for users. These frequencies are synthesized from a common source and are maintained in the exact ratio 1, 13/12, 10/9, 4/3. Phase coherence and emission timing are tightly controlled in the transmitter network. Table 1.1 lists Omega transmitter letter designations and locations.

A user wishing to navigate measures the phase difference between signals at one frequency from a pair of transmitters and thus establishes a line of position (LOP). Repeating the process with two more pairs of transmitters leads to a unique navigation fix. Navigational ambiguities can exist with Omega since any one phase difference corresponding to a pair of transmitters defines a family of hyperbolic LOPs. Along a baseline, LOPs occur every half wavelength. The region between adjacent LOPs is known as a lane and Omega accuracies are frequently described in units of centilanes (0.01 lane). The lane ambiguity problem can be alleviated by combining instantaneous measurements from two frequencies.

Omega is a VLF system and it is therefore subject to all the propagation anomalies normally associated with VLF. Some of the more important error sources associated with Omega are; (a)

Table 1.1
Omega Transmitting Stations

STATION LETTER DESIGNATION	LOCATION	LATITUDE/LONGITUDE
A	Aldra, Norway	66°25'N/13°08'E
B	Monrovia, Liberia	06°18'N/10°40'W
C	Haiku, Hawaii	21°24'N/157°50'W
D	LaMoure, North Dakota	46°21'N/98°20'W
E	La Reunion	20°58'S/55°17'E
F	Golfo Nuevo, Argentina	43°03'S/65°11'W
G	Gippsland, Australia *	38°29'S/146°50'E
H	Tsushima, Japan	34°37'N/129°27'E

*The Australia station is expected to become operational in 1981.

diurnal and seasonal ionospheric variations, (b) transient ionospheric phenomena such as Polar Cap Absorption (PCA) events and Sudden Ionospheric Disturbances (SIDs) that give rise to propagation anomalies, (c) modal interference, and (d) noise.

Diurnal and seasonal ionospheric variations cause phase shifts on the order of 50-100 centilanes at most user locations. These variations can be predicted and modeled to within a reasonable accuracy and are provided to users as algorithms within a receiver's navigation processor.

Sudden phase anomalies are associated with SIDs caused by solar flare x-rays. These are daytime events and typically last about fifty minutes. Solar protons, associated with large flares, may be guided into the polar regions and produce PCA events. These events may affect polar region propagation for several days.

Modal interference describes the effect that occurs when more than one waveguide propagation mode is excited by a radiated signal. When this happens, the modes received by a user combine constructively and destructively and cause anomalous signal variations. This phenomenon occurs most commonly near a transmitter and when the propagation path crosses a twilight region.

Noise at VLF is mostly of atmospheric origin, although manmade noise can dominate in certain local regions. Noise effects can be diminished by integrating received signals over long periods, but the period of integration must be consisent with dynamic requirements of the user and expected transients in the signals.

Airborne radio reception at VLF is susceptible to noise caused by a phenomenon known as precipitation static, or P-static. P-static is associated with precipitation of ice particles on the metal skin of the aircraft that results in a buildup of electrostatic charge. The problem occurs primarily in systems that use E-field antennas, and can degrade Omega performance significantly. Section 3.2 discusses a special experiment designed to study this problem.

Quoted accuracy for Omega under nominal conditions is 1-2 NM [1,3,4]. Nominal conditions include the use of propagation prediction corrections (PPCs) to compensate for regular ionospheric variations, the absence of SIDs and PCA events, the absence of modal interference, the absence of excessive noise, and the adequate compensation of platform dynamics. Under less favorable conditions, Omega accuracy degrades, either gradually or in the form of lane ambiguities. Marine users on the high seas may find 1-2 NM accuracy acceptable and may even be able to tolerate limited perods of degraded accuracy. On the other hand, marine navigation in restricted waterways and aircraft navigation near terminals requires a higher level of accuracy and reliability.

The Differential Omega concept arises from the observation that many Omega navigation errors associated with propagation effects are highly correlated in time and space. For example, consider two Omega users navigating independently a short distance apart. The absolute error of each user's fix may be 2 NM, but the relative positional error will be perhaps an order of magnitude smaller. If a real-time data link could be established between the two users so that both sets of phase measurements could be correlated, then the two users could maintain a positional relationship accurate to within a fraction of a mile. This concept is known as Relative Omega. If we now consider that one user remains fixed at a known, surveyed location and provides real-time phase measurement data to the second user, then the second user can obtain absolute navigational accuracy to within a fraction of a mile. This concept is known as Differential Omega, the fixed user is called the monitor and the moving user is called the navigator.

The ability of Differential Omega to eliminate correlated errors points to a significant practical benefit, namely that the navigator need not provide or compute PPCs since such corrections are intrinsic to the differential corrections received over the data link.

Differential Omega, as a concept, has been recognized for at least 14 years [1-3]. Experimental verification of the concept has been somewhat limited [4-5]. Swanson and Davey [5] have described the results of a marine Differential Omega experiment conducted in the coastal waters off Galveston, Texas. Figure 1.1 illustrates results of navigational accuracy as a function of range from the monitor obtained by Swanson and Davey. These results indicate an accuracy of 0.2 NM at close ranges and a gradual degradation in accuracy with increasing range. At very long ranges, the error obtained with Differential Omega may exceed the error obtained with ordinary Omega. The radius of the applicable region is limited both by the propagation range of the data link and the tolerable decorrelation error.

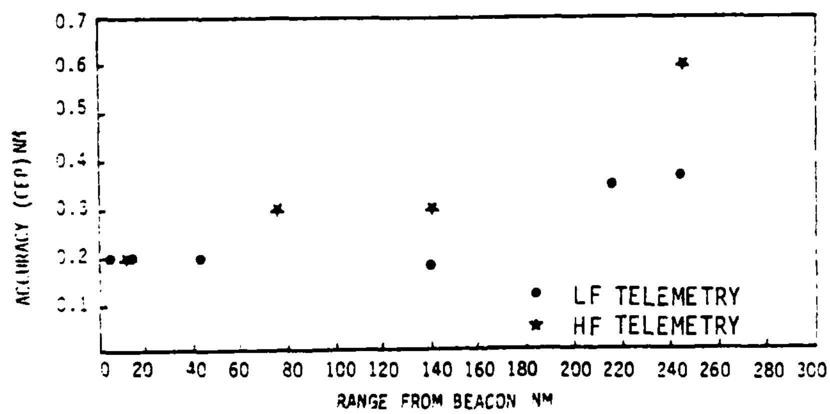

Figure 1.1 Differential Omega Accuracy vs. Range from Monitor [5]

Navigational aids for aviation users include a broad spectrum of systems, that range from a simple non-directional beacon (NDB) to VOR and DME (and its military counterpart, TACAN) and radar. The most comprehensive and complex systems such as radar and VOR/DME are expensive, require frequent maintenance and consume a high level of electrical power. Less comprehensive navigational systems such as NDBs require very little maintenance and power and are relatively inexpensive. Throughout much of Alaska and Northern Canada, many remote communities depend entirely on aviation for supplies and transportation to and from the outside world. The facilities available at these remote sites frequently consist of little more than a landing strip large enough to accomodate a small aircraft. Energy is always a problem at such sites since fuel must be flown in, consequently, most remote airstrips do not even have the luxury of a colocated NDB. The costs of providing VOR/DME at every remote airstrip in North America would be prohibitive. Even NDBs with their lower costs and more modest energy requirements do not offer a completely attractive solution, since an NDB provides directional information only, and in order to be effective, must be located at the site being sought by the navigating aircraft.

The Federal Aviation Administration and Transport Canada have been seeking a solution to the requirement for a low-cost, accurate navigation system that will meet the needs of small aircraft flying in and out of remote locations in the northern part of the continent.

Differential Omega is considered to be a potential answer to this requirement. Studies [6] have shown that Differential Omega in the Alaska/Yukon region should be able to provide two-dimensional navigation accurate to within a fraction of a mile over a region within a hundred-mile radius from a monitor. It has been suggested that it is practical to colocate a Differential Omega monitor and an NDB and to use the NDB as a carrier for the differential correction information. This means that Differential Omega monitors could be deployed at existing NDB sites at relatively low cost and at very little increase in electrical power requirements. It also means that NDBs used in conjunction with Differential Omega would not have to be located at every airstrip, but could support navigation over a region that might include several airstrips.

1.4 PROJECT MILESTONES

Some of the important milestones that have occurred during the course of Task V are as follows:

- May 1979. One set of Differential Omega avionics was delivered to Transport Canada. Monitor station equipment was delivered to Anchorage.

- October 1979. An avionics package was installed in the FAA aircraft at Anchorage and was test flown.

- January 1980. Differential Omega navigation was flight tested from Anchorage. Results suggested successful navigation using Differential Omega and indicated an achieved range of 40 miles on the data link from the monitor station to the aircraft.

- March 1980. A flight test was conducted during which software and interface problems were encountered.

- June 1980. A Differential Omega flight test yielded successful reception of the monitor signal to a maximum range of 94 miles. Software and interface problems negated any navigation results.

- October 1980. Extensive flight tests and ground tests were conducted. Highlights of the tests included a successful first test of navigation using the Deadhorse Monitor, the first successful use of digital tape for recording the data, the acquisition of extensive monitor data and the achievement of a 198-mile range of operation on the data link. Problems in software and instrumentation limited the accuracy performance of the system, however.

- February 1981. Flight tests demonstrated navigational accuracies of 0.1 mile to 1.0 mile using Differential Omega.

- April 15, 1981. An invited paper on Differential Omega was presented at the Ionospheric Effects Symposium in Alexandria, Virginia.

- August 1,1981. Task V is completed and a final report is submitted.

II. TECHNICAL APPROACH

2.1 PROJECT MANAGEMENT

This project, the development and evaluation of a Differential Omega system, was conceived to be a joint effort between Transport Canada and the FAA. SCI was placed under contract to the FAA (DOT-FA75-WA-3662) to represent the FAA in the technical performance of the project. SCI, in turn, placed Tracor under contract to perform specific tasks in support of the project.

The allocation of tasks under this project and the main participants are as follows:

- Transport Canada developed the monitor station subsystem, including the required software, and also provided on-site support for installation and operational testing of the monitor station.

- Tracor provided three Model 7620 Omega receivers that were modified appropriately for Differential Omega operation, where the required modifications involved both hardware and software. Tracor also provided flight test support in Alaska.

- SCI provided overall system design, System Integrator development, flight test direction, data analysis and project management.

2.2 SYSTEM CONFIGURATION

The project described herein has been primarily operational rather than research oriented. The location of the flight tests in Alaska has the interesting characteristic that the azimuth directions of signals from stations A, C, D, and H intersect at nearly right angles, as illustrated by Figure 2.1.

The experimental concept called for the use of operational NDB signals as carriers for differential correction data. NDB's represent a convenient means, but not the only means, for providing a data link for Differential Omega, other possibilities are VOR, special HF transmitters, etc. NDBs in Alaska have a primary mission of direction finding (DF) and a secondary mission of providing weather broadcast. The weather information is contained in an audio (voice) signal that is amplitude-modulated onto the beacon carrier. The NDBs that were used in this experiment were modified so that, when used for Differential Omega telemetry, the voice signal was replaced with a 1-kHz side tone, and the side tone was bi-phase modulated with digital error signals derived from the Omega receivers. The use of Differential Omega thus precluded the availability of weather information from these NDBs and was viewed as a minor inconvenience. The NDB identification code was maintained during Differential Omega operation. A ground rule for the Differential Omega experiment was that the use of the NDBs for telemetry was not to degrade the quality of the DF signals so as to compromise the primary mission of the NDBs. At all times during this experiment, NDBs were operated in compliance with ICAO requirements [1].

Figure 2.2 illustrates the experimental configuration. The avionics were mounted on a special pallet in an FAA Convair 580

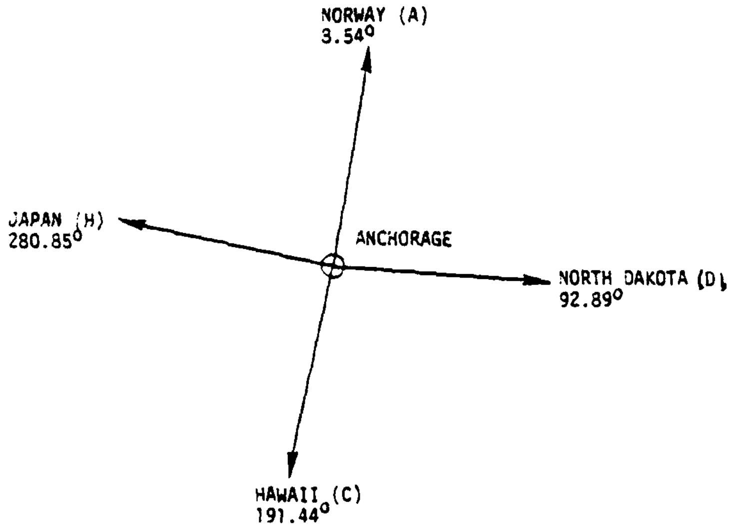

Figure 2.1 Azimuth Direction to Omega Transmitters from Anchorage, Alaska

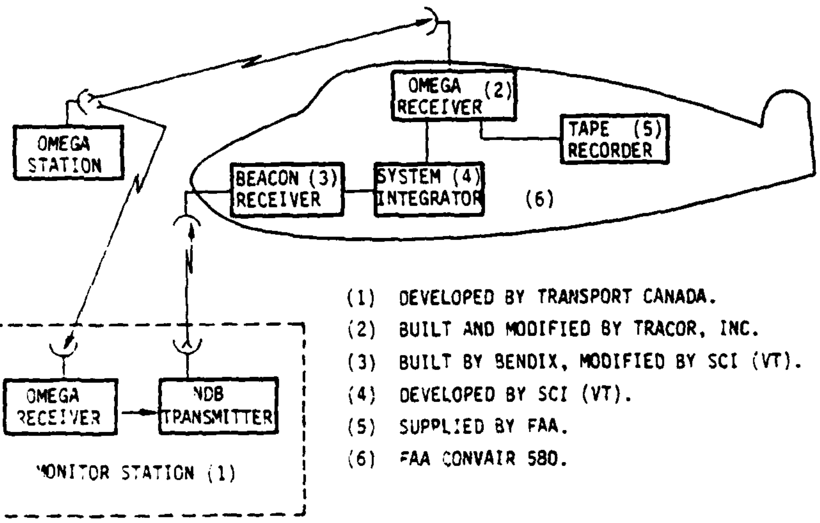

Figure 2.2 Differential Omega System Configuration

aircraft based at Anchorage International Airport. Monitor stations were located at Merrill Field about 5 miles east of Anchorage International, and at Deadhorse, on Prudhoe Bay. Omega receivers and NDB transmitters were nearly colocated at both monitor stations. Reference location information for the navigator aircraft was provided by identified pads for ground tests, and by DME instrumentation for flight tests. Figures 2.3 and 2.4 illustrate the geography of the experiment and available instrumentation. These figures display every VOR/DME within 250 miles of Anchorage and Deadhorse. Although these navigation aids provide reasonably redundant coverage for enroute navigation of aircraft flying at high altitudes, their line-of-sight range is proportionately less at low altitudes so that they degenerate to short-range homing aids for general-aviation users who are limited to altitudes less than about 10,000 ft. It can be seen that for the low-altitude user, there are vast areas in Alaska where there is no effective coverage by VOR/DME.

It is instructive to provide a brief description of the operation of the monitors and the determination of differential corrections. We begin by expressing the known location of a monitor in terms of standard phases. A standard phase is defined by a monitor location, an Omega transmitter location, an Omega frequency and a geodetic model. First, the propagation range between a monitor and an Omega transmitter is calculated using an appropriate geodetic model. Next, the propagation range is expressed in wavelengths for the particular frequency. Finally, the integer number of wavelengths is discarded and the fractional wavelength is retained. This fractional wavelength is known as a standard phase and it is a highly sensitive indicator of monitor location. Standard phases from three Omega transmitters define the location of a monitor uniquely except for the lane ambiguity discussed earlier. Tables 2.1 and 2.2 list standard phases for the Deadhorse and Anchorage monitor stations. These values were calculated using a WGS-72 geodetic model and assuming propagation

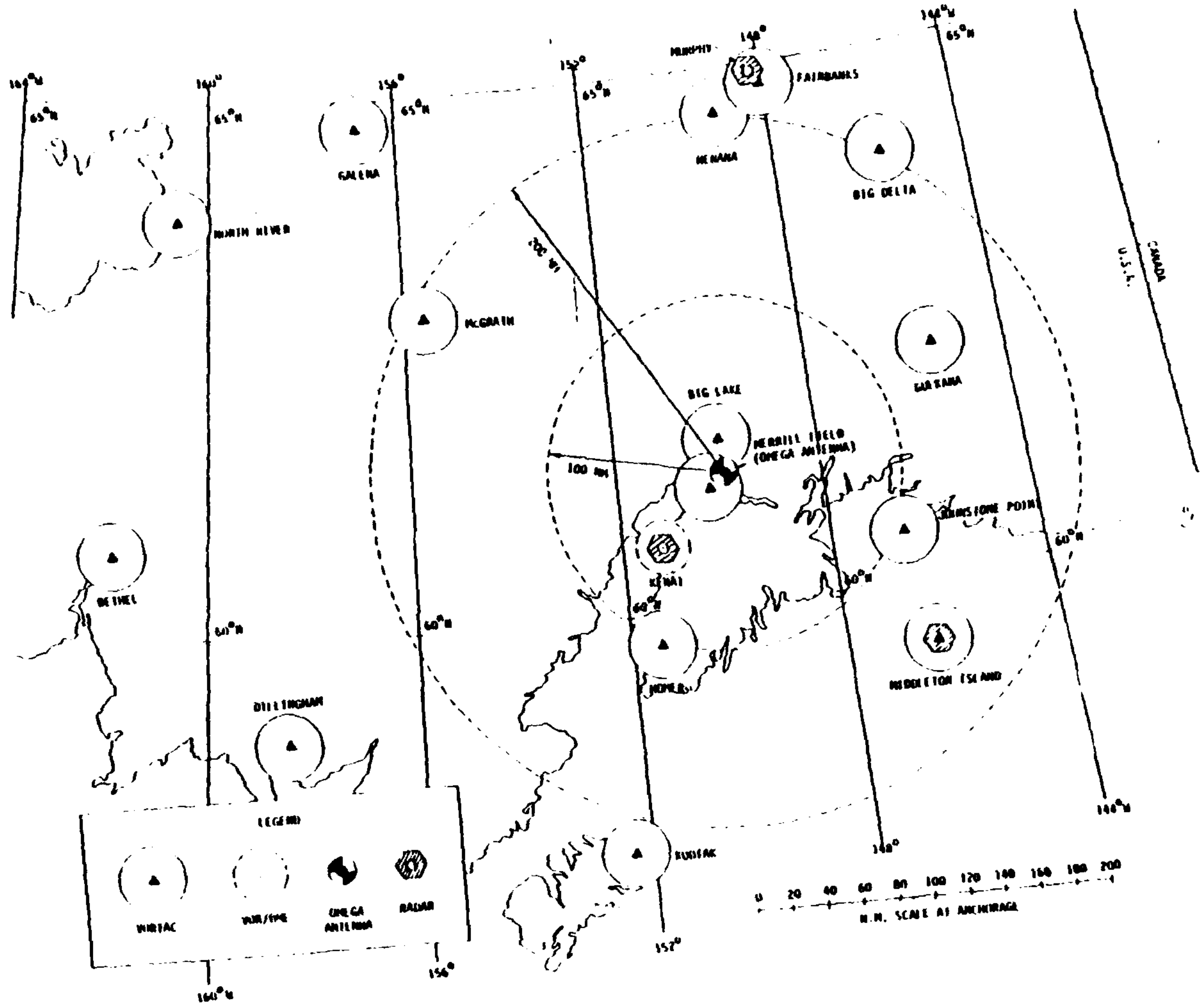

Figure 2.3 Instrumentation Available for Flights Near Anchorage

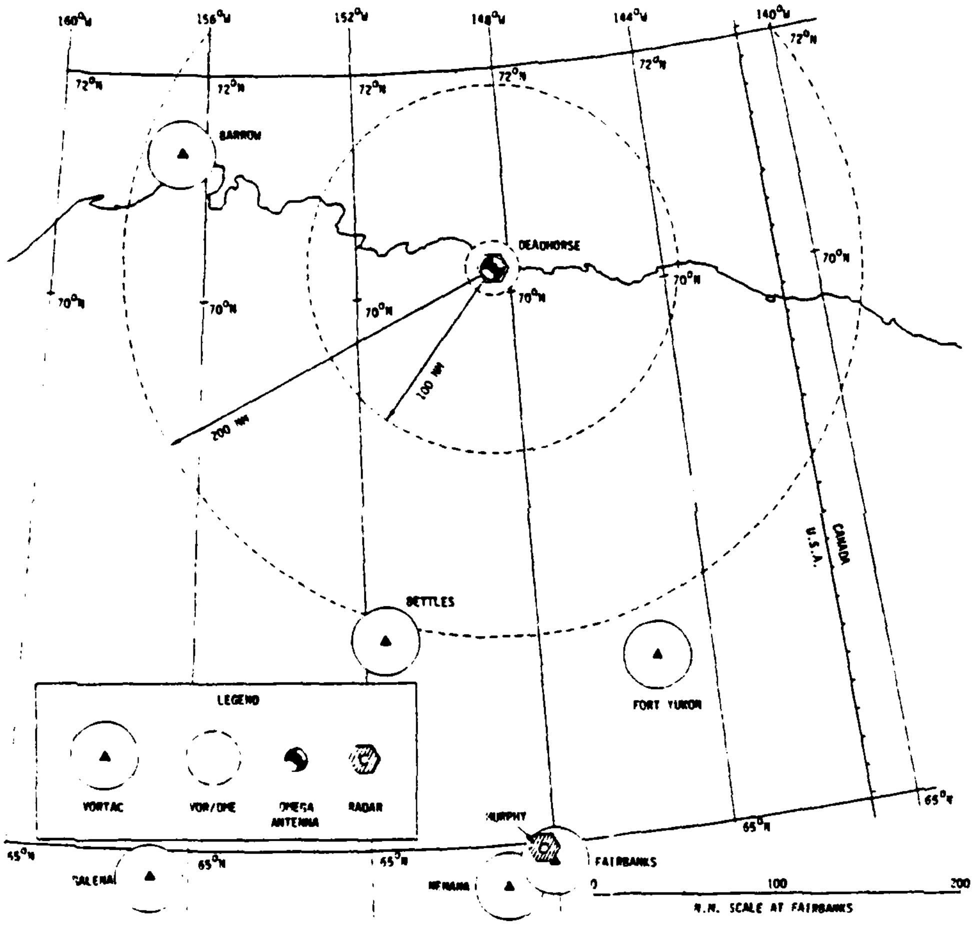

Figure 2.4 Instrumentation Available for Flights Near Deadhorse

Table 2.1
Deadhorse Standard Phases in Fractions of Lanes

FREQUENCY	OMEGA TRANSMITTERS			
	A	C	D	H
10.2	.037	.157	.791	.088
13.6	.676	.592	.881	.255
11.3	.614	.986	.033	.349

Table 2.2
Anchorage Standard Phases in Fractions of Lanes

FREQUENCY	OMEGA TRANSMITTERS			
	A	C	D	H
10.2	.894	.439	.804	.953
13.6	.949	.503	.550	.085
11.3	.973	.507	.757	.729

velocities of 161924.60 NM/s at 13.6 kHz and 162393.88 NM/s at 10.2 kHz.

We next consider the arithmetic involved in providing a differential correction. Each monitor receiving system consisted of three Omega receivers, a Rubidium frequency standard, a 1-kHz subcarrier modulator, and a microcomputer. The frequency standard was used to provide stable monitor receiver references at 10.2, 11.33 and 13.6 kHz. Each Omega receiver was tuned to one of the three frequencies and usually received signals from Stations A, C, D, and H. At each frequency, the phase of a signal from one transmitter was compared with the phase of the locally synthesized signal, and the phase difference was transmitted as a correction. We have, for each signal,

$$\phi_s - (\phi_m - \phi_r) = \Delta \tag{2.1}$$

where ϕ_s = standard phase

ϕ_m = measured signal

ϕ_r = local reference phase

Δ = differential correction.

Ideally, the local reference phase ϕ_r would be identical to the phase at the Omega transmitter in which case Eq. (2.1) would express the relationship: True Range - Measured Range = Range Error. In fact, the local reference phase differed from the transmitter phase by an arbitrary unknown value. Because of the precision of the local frequency reference, however, the unknown phase difference between the monitor local reference and the transmitter varied quite slowly. The local reference phase disappeared in the process of forming an LOP which, as we have stated, involved forming phase differences between signals measured from two transmitters. If we apply this process to Eq. (2.1) for any two Omega transmitters labeled No. 1 and No. 2, we have

$$\Phi_{s1} - (\Phi_{m1} - \Phi_r) = \Delta_1 \qquad (2.2)$$

$$\Phi_{s2} - (\Phi_{m2} - \Phi_r) = \Delta_2 \qquad (2.3)$$

Subtracting Eq. (2.3) from Eq. (2.2) yields a quantity $\Delta_1 - \Delta_2$ which was a correction to be applied to an LOP and which was independent of the local reference phase at the monitor.

In this configuration each phase correction as expressed by Eq. (2.1) was transmitted via the NDB. The appropriate combinations, as expressed by the difference $\Delta_1 - \Delta_2$, are performed by the navigation computer within the avionics according to the LOPs being computed. A complete correction message was transmitted every ten seconds and consisted of twelve correction values; i.e., four transmitters at three frequencies each.

Appendix A describes the format of the Differential Omega correction message that was transmitted over the NDB data link. Appendix B describes the software resident in the System Integrator and Appendix C contains a schematic diagram of the System Integrator electronics.

III. FIELD TEST MEASUREMENTS AND RESULTS

3.1 GENERAL

Field testing of Differential Omega under this project took place in January, March, June and October 1980 and February 1981. Field testing in Alaska has presented many difficulties, foremost of which have been the following:

- The sites of the field experiments have been Anchorage and Deadhorse, Alaska, whereas the major participants in the project have been headquartered in Ottawa, Canada; Austin, Texas; and Palo Alto, California. Each series of field tests thus required considerable coordination and scheduling, and involved a significant expense for travel, per diem, etc.

- The amount of dedicated flight time authorized for this project was extremely limited. As a practical matter, then, acquisition of flight data was largely constrained by the availability, routing and scheduling of commissary flights. Flights to Deadhorse, for example, were infrequent so that data for the Deadhorse monitor system are quite limited.

- The environment in Alaska is harsh. On two occasions, for example, external electrical problems disabled the monitor station (once at Anchorage, once at Deadhorse) and negated flight tests then underway.

- The Differential Omega equipment, both in the aircraft and in the ground stations, was installed for the specific purpose of the Differential Omega project. Consequently the equipment was not operated or maintained during the long periods between field tests. As a result, each series of field tests inevitably involved several days of trouble-shooting and repair before valid Differential Omega tests could be performed.

- The remoteness of Alaska and the lack of sophisticated repair and data reduction facilities for project equipment resulted in extensive delays in effecting certain repairs and transcription of data tapes. These delays had a significant cumulative effect on the project schedule.

In terms of useful data, the two most important field tests took place during October 1980 and February 1981. It is instructive to consider these test sets separately, after which the general implications of the results will be discussed.

3.2 OCTOBER 1980 FIELD TESTS

Field tests took place during the period October 16 through October 24, 1980, and were conducted in three sets. The first set involved Differential Omega navigation while the aircraft was parked at a known location. Samples of navigational solutions taken at ten-second intervals from the avionics were recorded for fifteen minutes each on several occasions, yielding statistical performance data at a fixed location free of the complications associated with flight testing. The second set of tests consisted of recording Omega phase data in one-minute samples for several days as received by the Deadhorse and Anchorage monitors. The measurement data taken from each monitor provided information on diurnal variations in phase associated with regular ionospheric behavior. Comparison of the phase data between the two monitors yielded information on range decorrelation error for Differential Omega. The third set of tests took place during routine flights of the aircraft from Anchorage International Airport. These tests yielded information on in-flight performance of Differential Omega in terms of accuracy and maximum range of the data link. It is instructive to consider each of these sets of tests in detail.

3.2.1 Differential Omega Ground Tests

The Differential Omega ground tests were performed as follows. The aircraft was parked on a pad at Anchorage International Airport. The monitor computer at Merrill Field was loaded with the appropriate standard phases. The system was operated in the Differential Omega mode using correction data from the monitor at Merrill Field. Navigation solutions at the aircraft based on ten-second sampling periods were recorded for fifteen minutes. The standard phase values in the monitor computer were then modified to simulate a displacement of the monitor two miles north of its actual position. Ten-second samples of navigation solutions at the aircraft were again recorded for fifteen minutes. The standard phase values in the monitor computer were then modified to simulate a displacement of the monitor two miles west of its actual position. Ten-second samples of navigation solutions at the aircraft were again recorded for fifteen minutes. The three sets of measurements were performed twice, once between 11 AM and 12 noon, and once between 6 PM and 7 PM local time.

Figure 3.1 illustrates an example of the results obtained from the Differential Omega ground tests. The origin of the plot is defined to be the pad location, 61°10'22"N, 149°58'06"W, and the plotted points represent the navigation solutions obtained during the tests. The three groups of solutions correspond to the three sets of standard phases loaded into the monitor computer. The results shown in Figure 3.1 are representative of all results obtained from the Differential Omega ground test.

Analysis of the results of these tests yields the following observations:

(1) Random scatter of the ten-second navigation solutions was about 0.25 nautical miles, 2-DRMS [3]. Since the sampling rate was not adjustable, there was no opportunity to investigate the dependence of random error statistics on sampling period.

(2) Mean error of the test data was about 0.5 nautical miles eastward, 0.25 nautical miles northward. This error is not attributed to Differential Omega. It is probable that the mean error is caused by uncertainties in the assumed locations of the monitor or the aircraft pad.

(3) Mean error at any single location can be zeroed out by adjusting the standard phases at the monitor. Adjustment of the mean error had no observable effect on the random error component of the navigation solutions for these tests.

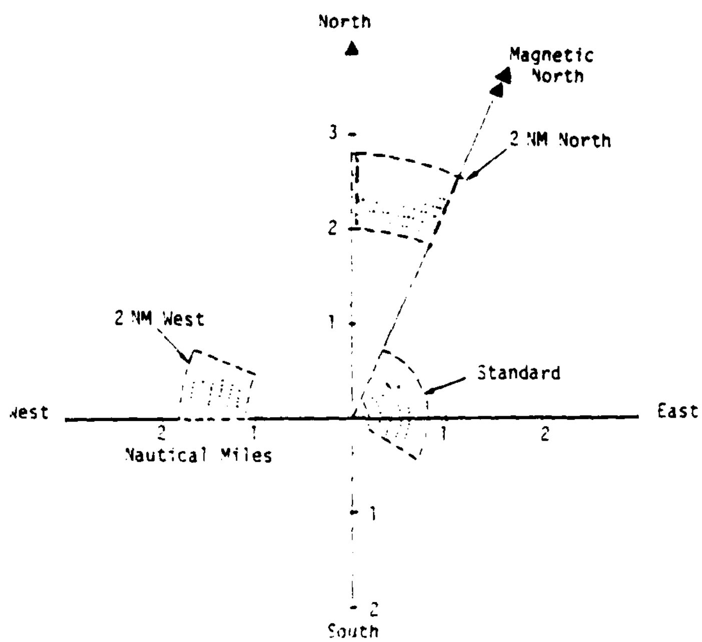

Figure 3.1 Representative Results of Differential Omega Ground Tests, October 19, 1980. (Dashed lines contain 95% of all data points.)

3.2.2 Monitor Phase Correlation Tests

Received Omega phases at the Merrill Field and Deadhorse monitors were sampled and recorded at one-minute intervals nearly continuously for several days during the experiment. Phase data at each monitor yielded information on (a) long-term drift of the monitor frequency standard relative to the standard of the Omega transmitter network, (b) diurnal phase variations associated with regular ionospheric effects, and (c) the presence of phase anomalies with periods greater than one minute. In addition, comparison of phases between the two monitors yielded information on the range decorrelation error of Omega navigation solutions between the two monitor locations.

Figure 3.2 illustrates 24 hours of phase data recorded at the Merrill Field and Deadhorse monitors. Curves are presented for signals at 10.2 kHz and 13.6 kHz from stations A, C, and D. Station B was temporarily off the air during these measurements. Phase is measured modulo one cycle and cycle rollovers are reflections of continuous phase variations.

Examination of Figure 3.2 reveals the following features:

(1) There is great similarity in the gross behavior of corresponding signals at 10.2 kHz and 13.6 kHz although fine structure appears to be uncorrelated.

(2) Diurnal phase variations are most pronounced and most regular from station D, and least pronounced and least regular from station A. These observations are consistent with the facts that propagation from D is essentially through midlatitudes along a meridian where ionospheric behavior is well behaved and daily solar zenith angle variations are large; whereas propagation from A is through the polar cap which is less regular and where daily solar zenith angle variations are small.

(3) There is evidence of a slow (one-half cycle per day) drift in the phase of the Deadhorse frequency standard with respect to the standard of the Omega transmitter network. This effect is evident at both 10.2 kHz and 13.6 kHz. This is not a serious

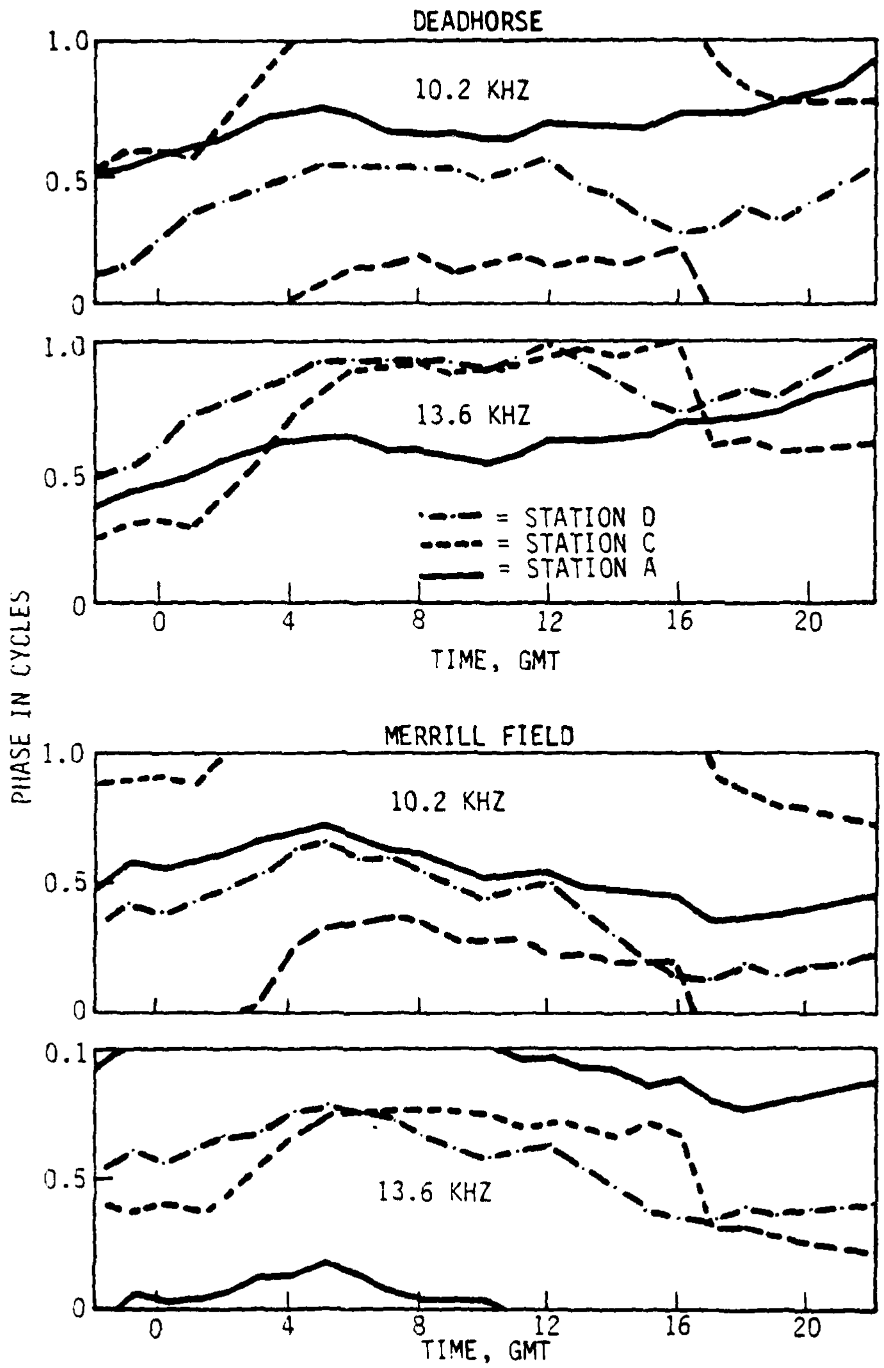

Figure 3.2 Omega Monitor Station Phase Measurements, October 23, 1980

problem since the differential nature of the navigation correction cancels the slow drifts out. It does not correspond to a frequency offset of roughly 3 x 10^{-10} in the monitor station's standard. With proper maintenance the standard is capable of being set to $\pm 2 \times 10^{-12}$ so this drift would not even be seen in an operational system. Any drift at Merrill Field is much smaller and is not readily discernable over a 24 hour period.

(4) No pronounced phase anomalies are evident at either monitor. The data do not permit the observation of phase fluctuations with periods less than one minute.

Comparison of the phases received at the two monitors can provide information on the decorrelation of Omega signals between the two monitors. The degree of decorrelation is a direct measure of the utility of Differential Omega over the distance between the two monitors.

The description of range decorrelation can be approached in the following way. Suppose, using the monitor at Merrill Field, one formed a differential correction from signals at 10.2 kHz received from stations A and C. Using a form of Eqs (2.1) through (2.3), one obtains

$$\delta_{ACM} = \Delta_{AM} - \Delta_{CM} \qquad (3.1)$$

where δ_{ACM} is a differential correction to the A-C LOP formed at Merrill Field and Δ_{AM} and Δ_{CM} are obtained from Eq. (2.1) as applied to signals from stations A and C, respectively. The number represented by δ_{ACM} will be applied by a navigator as a differential correction to the A-C LOP formed by the navigator. The navigator then expects that the corrected LOP will be nearly error-free. The A-C LOP can be combined with two other LOPs in the navigator's computer to form the desired fix. Let us now repeat the process, using the Deadhorse monitor. We have, analogous to Equation (3.1)

$$\delta_{ACP} = \Delta_{AP} - \Delta_{CP} \qquad (3.2)$$

where subscript P refers to the Deadhorse monitor. Let us now imagine a navigator hovering directly over the Deadhorse monitor who purports to navigate with Differential Omega using either the Merrill Field corrections described by Eq. (3.1) or the Deadhorse corrections described by Eq. (3.2). If there were perfect correlation between Merrill Field and Deadhorse, the result should be independent of which monitor is used, thus perfect correlation implies that, at each instant of time, $\delta_{ACP} = \delta_{ACM}$. The extent of disagreement between the two sets of differential corrections is, therefore, a measure of the lack of correlation between the two locations and may be described as range decorrelation error for the pair of locations.

Figure 3.3 illustrates values of $\delta_{ACP} - \delta_{ACM}$, $\delta_{ADP} - \delta_{ADM}$ and $\delta_{CDP} - \delta_{CDM}$; that is, the differences between corresponding LOP corrections obtained at Deadhorse and Merrill Field for the three possible pairs AC, AD and CD. The plotted values may be interpreted as measures of range decorrelation errors; that is, the navigation errors one should expect near one monitor while using correction values from the other monitor. Range decorrelation errors between Deadhorse and Merrill Field are seen to exhibit the following characteristics:

(1) Gross behavior is similar between 10.2 kHz and 13.6 kHz.

(2) A diurnal pattern is evident for each LOP, but the pattern is complex and is not the same for all LOPs.

(3) The total range of decorrelation error observed during the 24-hour period is less than ± 0.2 cycles ($\approx \pm 2$ NM). The maximum excursion of any LOP error is about 0.2 cycles ($\approx \pm 2$ NM).

Although Deadhorse and Merrill Field are separated by about 550 NM, which is a much greater range than is considered for Differential Omega validity, the results illustrated by Figure 3.3 suggest that even at this range, the accuracy achievable from Differential Omega would be comparable to that achieved with

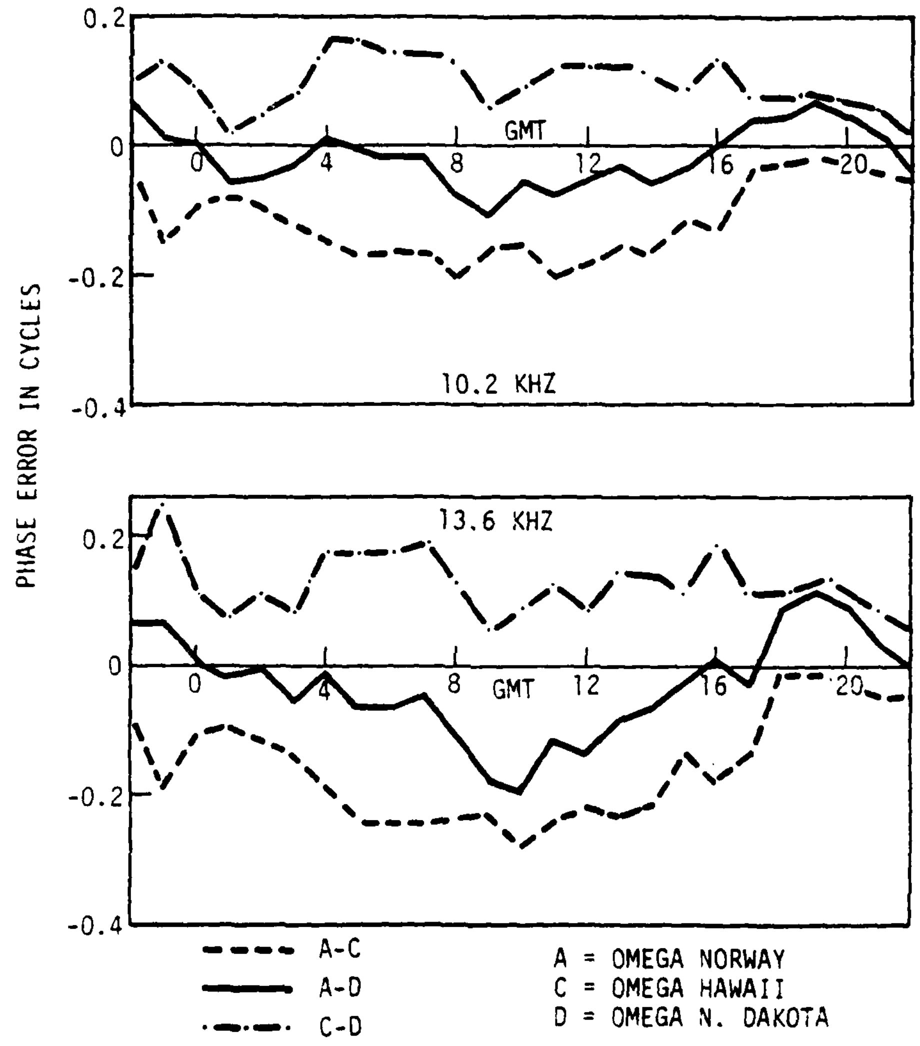

Figure 3.3 Decorrelation Errors Between Deadhorse and Merrill Field Monitor Stations, October 23, 1980

ordinary Omega, and since range decorrelation error is expected to be roughly proportional to data-link range, Differential Omega accuracy should be superior to ordinary Omega accuracy for all data-link ranges less than 550 NM.

3.2.3 Differential Omega Flight Tests

Flight tests were performed to verify Differential Omega operation and performance under actual flight conditions. The flight tests provided information on two primary indicators of performance; maximum range of the data link and accuracy of the navigation.

Four round-trip flights out of Anchorage International Airport were flown during the experiment, as follows: October 16, Anchorage to Galena to Anchorage; October 17, Anchorage to McGrath to Anchorage; October 22, Anchorage to Bettles to Anchorage; October 23, Anchorage to Deadhorse; October 24, Deadhorse to Anchorage. Table 3.1 lists the flights and the maximum ranges of the data link that were observed. Maximum range was defined in terms of received data link signal quality according to an algorithm that measures error rate in the differential correction data. When error rates exceeded a preset threshold of 2.5×10^{-3}, the differential correction message was rejected and the maximum range of the data link was deemed to have been exceeded. Characteristics of the data link are discussed at greater length in Section IV.

Table 3.1
Observed Differential Omega Maximum Range in NM

DATE	MONITOR	OUTBOUND FLIGHT	INBOUND FLIGHT
October 16	Merrill Field	55	107
October 17	Merrill Field	128	151
October 22	Merrill Field	68	103
October 23	Merrill Field	44	---
October 23	Deadhorse	---	No data
October 24	Deadhorse	198	---
October 24	Merrill Field	---	147

The results shown in Table 3.1 suggest the following:

(1) Maximum range of the data link is variable by a factor of two from day to day. Since the routes and times associated with the flights on October 16, 17, and 22 were similar, the most likely explanation for the daily variation appears to be the varying level of P-static noise encountered by the aircraft. In fact, concurrent measurements of P-static in a collateral experiment suggest support for this explanation.

(2) The smallest maximum range observed during this experiment was 44 NM. There is no reason to believe this figure could not be improved by using higher levels of modulation at the monitor NDB or by means of other changes designed to optimize the performance of Differential Omega.

(3) There is a strong indication of a non-uniform gain pattern in the beacon antenna of the aircraft. The ratio of average maximum range on inbound flights to average maximum range on outbound flights for the flights on October 16, 17 and 22 is about 1.4 and suggests a front-to-back gain ratio of 3 dB in the aircraft antenna pattern.

Measurements were made to determine the accuracy performance of Differential Omega during the flights of October 16-24. The technique used was to record simultaneously samples of DME measurements and navigation outputs of the Omega equipment. DME measurements were of slant range from the aircraft to the DME transponder being interrogated by the aircraft. DME accuracy is considered to be about one percent of the range being measured.

The accuracy measurements were hampered by several problems in the aircraft. First, data from one of the two DMEs failed consistently to record properly, thus determinations of Omega accuracy could only be made along the direction defined by the other DME measurement. Second, true airspeed data from the aircraft to the Omega were not available for this experiment. True airspeed is an essential input to the Omega system, and missing or incorrect data cause significant error in the navigation solution. In the absence of the normal true airspeed signal, this essential input could be provided only by keying-in an estimated value through the front panel controls of the Omega receiver.

During the analysis following the experiment, only two cases were found in all the recorded flight data where keyed-in estimates appeared to be reasonably accurate. Figure 3.4 illustrates navigation performance of Differential Omega for these two cases, where the plotted values represent the component of Omega error in the direction defined by the DME measurement.

The results illustrated in Figure 3.4 suggest the following:

(1) In both cases, the only measured components of navigation errors are along track; that is, parallel to the flight path of the aircraft. Along-track navigation performance of airborne Omega is more sensitive than cross-track navigation performance to errors in true airspeed information. The results displayed here are thus conservative with respect to two-dimensional error performance of Differential Omega.

(2) Both measurements indicate a nearly monotonic increase in error with increasing range from the monitor. This trend is consistent with the results obtained by others [5] and illustrated in Figure 1.1, although the magnitude of error in the present experiment is considerably larger than that observed in earlier work.

3.2.4 P-Static Noise Cancellation Tests

During the October 1980 flight tests, a special experiment was performed to test a proposed method for providing cancellation of P-static at VLF. The P-static experiment was not an integral part of the Differential Omega tests and was performed on a non-interference basis. Appendix D is the Final Report describing the results obtained during the experiment.

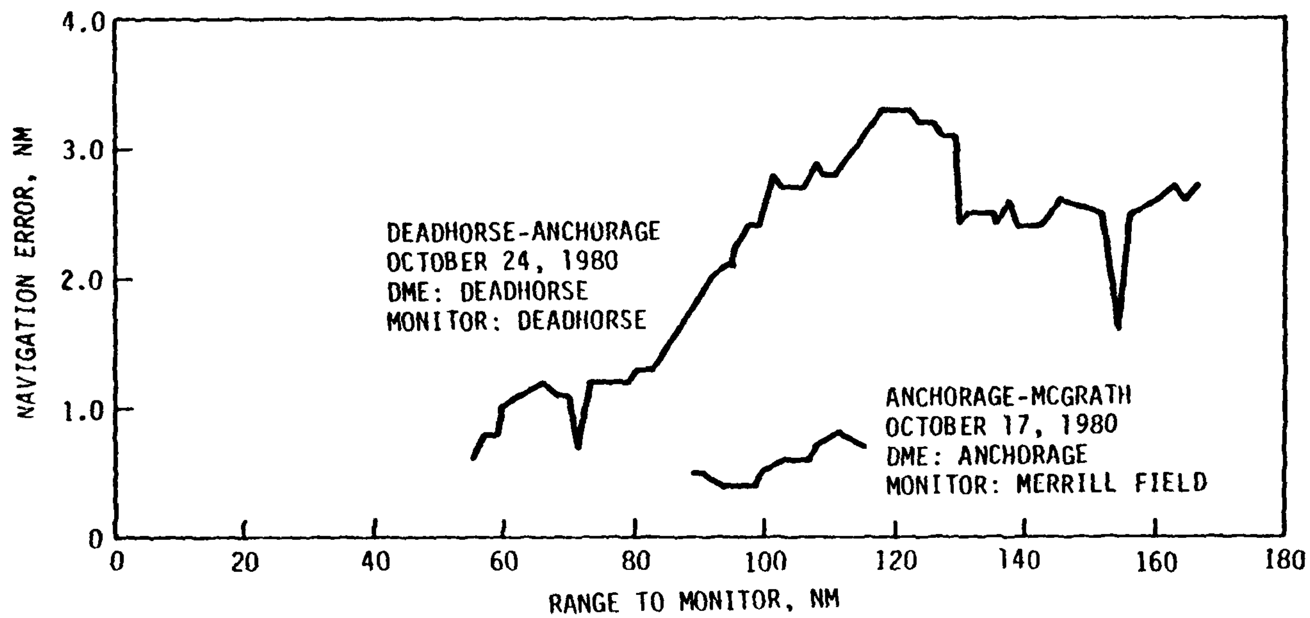

Figure 3.4 Inflight Differential Omega Navigation Errors

3.3 FEBRUARY 1981 FIELD TESTS

Field tests were conducted between 23 February and 27 February 1981. The first three days were spent troubleshooting and repairing equipment problems. The first Differential Omega flight test of the series took place during a commissary flight from Anchorage to King Salmon. Unfortunately, an electrical transient in the ground station power source disabled the beacon transmitter shortly after takeoff from Anchorage, thus negating any Differential Omega results that might otherwise have been obtained.

On 27 February another flight test of Differential Omega was attempted. The flight on 27 February was entirely dedicated; that is, Differential Omega test was the only purpose for the flight.

The test plan was to fly from Anchorage to Homer using the Kenai and Homer DME signals for references while performing area navigation enroute. After arriving at Homer, the plan called for flying a series of non-precision approach routes including procedure turns and flying according to the ILS localizer beam at Homer.

The data link contained significant static and finally became unusable at about 60 miles out of Anchorage. The flight proceeded to Homer and attempts were made to recover the data link but without success. The aircraft then proceeded to Big Lake where the data link was recovered and where several low-altitude overflights of the DME antenna were conducted. By this time the weather had cleared sufficiently to permit low-altitude flights at nearby Elmendorf Air Force Base. Several ILS approaches were then flown on the localizer beam at Elmendorf and a comparison was made between DME readings and Differential Omega readings using the DME antenna colocated with the Elmendorf localizer antenna.

Figure 3.5 illustrates the two-dimensional results obtained during the flight from Anchorage to Homer. In Figure 3.5, the tips of the arrows represent the aircraft positions determined by DME measurements from Anchorage, Kenai and Homer. The bases of the arrows indicate the Omega-inferred position of the aircraft at corresponding times. It can be seen that the Differential Omega error at 2209 GMT was about 5 NM (if we assume that the DME readings were error-free) and that the Differential Omega error decreases monotonically with time until 2219 GMT when the apparent error was less then 0.1 NM. At 2219 GMT the data link was lost, and Figure 3.5 indicates that, upon losing the data link, Omega accuracy degraded immediately.

The reason for the observed behavior is believed to be the combination of two factors. First, the Tracor 7620 Receiver/Processor has a convergence time of about 20 minutes after utilization. Secondly, just before takeoff from Anchorage, the system lost power while switching from a ground source to aircraft engine power, and so the processor had to be re-initialized after starting the aircraft engines. Since takeoff at about 2200 GMT took place immediately after starting the engines, the Omega solution had not completely converged by 2209 GMT when data recording began.

The most definitive measure of Differential Omega accuracy performance occurred during flights of the aircraft along the localizer beam at Elmendorf AFB. The Elmendorf localizer beam provides guidance for a low-altitude flight path oriented at 55° magnetic (80° true) with respect to north. Even in the presence of cross winds, a skillful pilot can maintain a cross-track error of less than 200 feet with respect to the center of the beam. In the present case, the aircraft maintained a cross-track error less than 150 feet during each approach along the localizer beam. Following the first and and second approaches, the aircraft proceeded in a counter-clockwise direction to intersect the beam again.

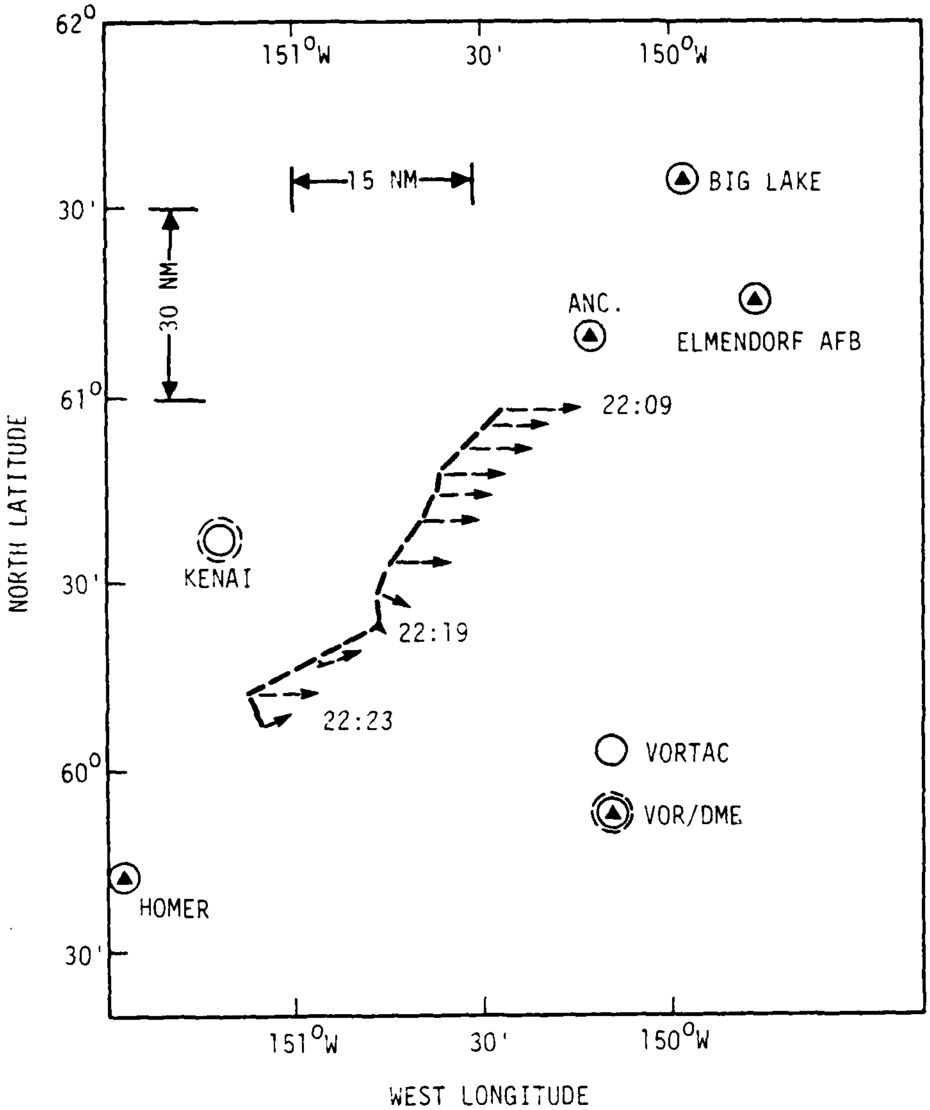

Figure 3.5 Two-Dimensional Differential Omega Errors During Flight from Anchorage to Homer on 27 February 1981

Figures 3.6 and 3.7 illustrate the results obtained during the second and third approaches along the Elmendorf localizer beam. In these figures the tips of the arrows describe the location of the aircraft at various times as determined by localizer and TACAN. The square dots at the bases of the arrows describe the Differential Omega solutions obtained at the same times.

The results illustrated in Figures 3.6 and 3.7 indicate the following:

(1) The magnitude of navigation error in the Differential Omega solutions varied from about 1.5 NM to about 0.25 NM during each approach along the beam.

(2) Performance of the Differential Omega system was repeatable on successive approaches.

(3) Differential Omega position solutions during a typical approach can be characterized by a position overshoot of about 1.5 NM followed by a monotonic decrease in error with an effective time constant of about two minutes. The position overshoot began as the aircraft executed a procedure turn counter-clockwise to enter the path of the localizer beam.

(4) A random error component of about 0.25 NM 2-DRMS appears to be superimposed on the transient response noted in (3).

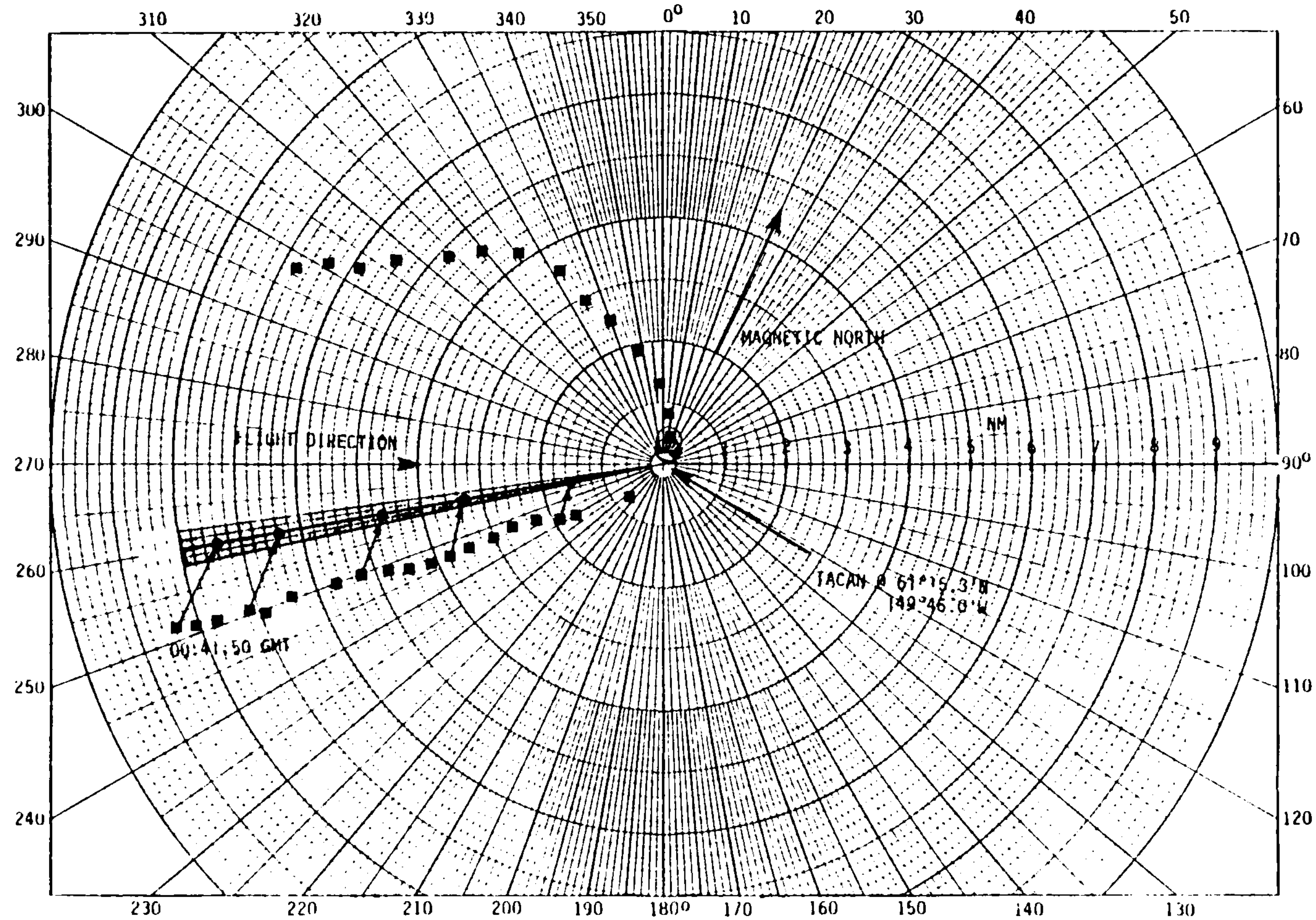

Figure 3.6 Comparison of Differential Omega and DME Positioning During Flights Along the Localizer Beam at Elmendorf Air Force Base on 27 February 1981, Second Approach

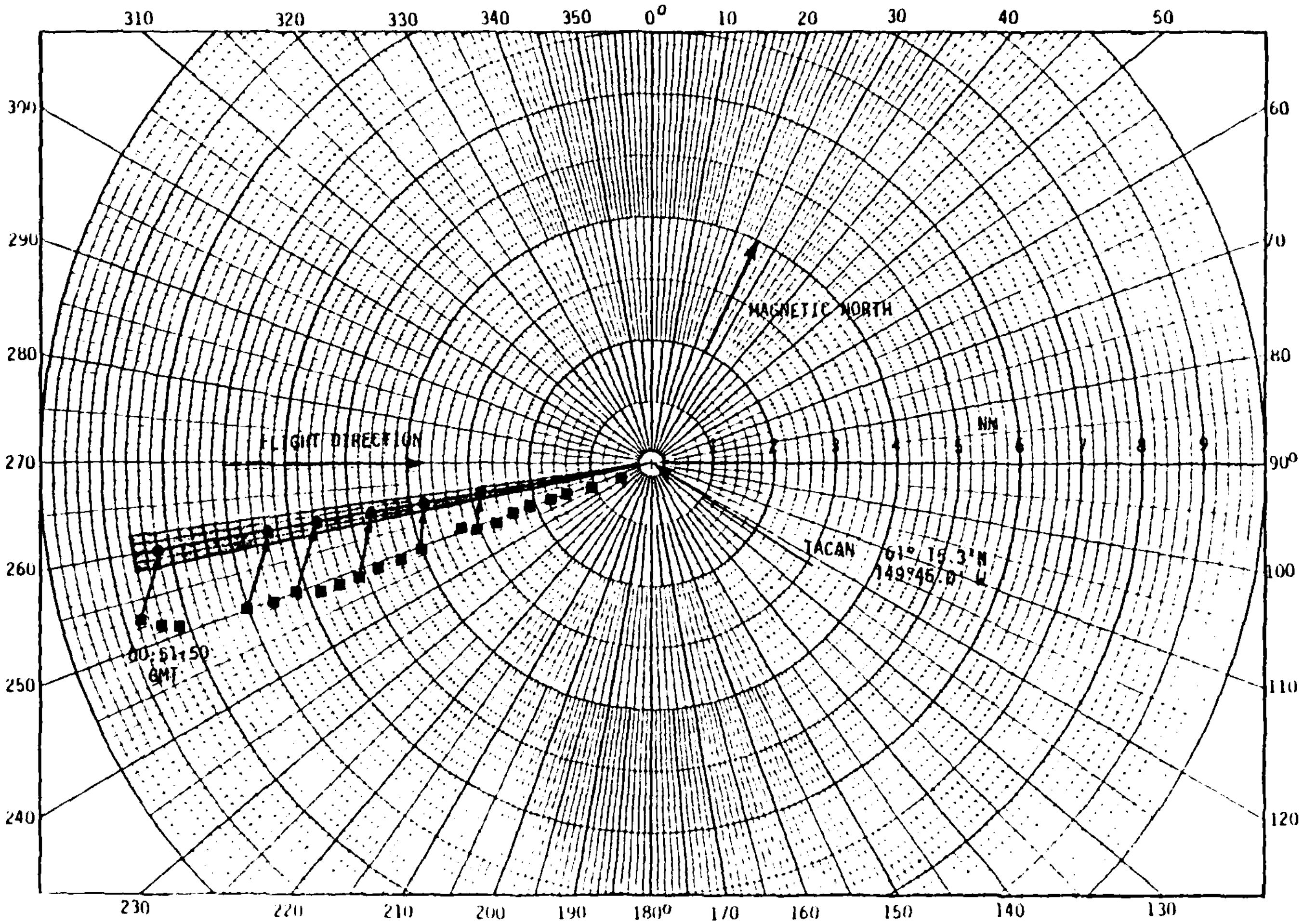

Figure 3.7 Comparison of Differential Omega and DME Positioning During Flights Along the Localizer Beam at Elmendorf Air Force Base on 27 February 1981, Third Approach

IV. DISCUSSION

The flight tests of October 1980 and February 1981 have provided answers to many of the questions that were stated at the beginning of this project, as well as to some questions that were probably not considered. It is instructive to pose two broad questions here that have been implicit in this project from the beginning, and to consider how the results of this effort answer, or fail to answer these questions. The questions are:

(1) What was the performance of the Differential Omega system that was tested in Alaska?

(2) What is the achievable performance of Differential Omega navigation in Alaska?

The first question, has been answered, to a large extent, by the test results described in Section III. The performance parameters measured during the field tests were navigational accuracy, data-link range, transient response and system reliability.

Navigational accuracy for the existing system was found to be characterized by a random error component of about 0.25 NM 2-DRMS (95%), under ideal conditions; that is, with a stationary navigator within 6 NM of the monitor station. Under conditions that included low altitudes, a short data-link range and procedure turns, the total error appeared to be characterized by a transient error component with a 1.5 NM peak and a 2-minute decay time constant, along with a steady-state random component of about 0.25 NM, 2-DRMS.

These results are of the form predicted theoretically [6] in terms of the polarity of the overshoot and the time constant of the recovery following a maneuver. However, the magnitude of the overshoot was much larger than has been predicted. The theoretical predictions were based on computer simulations of idealized conditions and did not include the effects of finite signal-to-noise ratio and instrumentation error. It should be pointed out that the transient behavior of the system following an aircraft maneuver should be the same whether the system is operating in ordinary Omega or Differential Omega. In other words, susceptability to aircraft maneuvers is not a characteristic that is specific to Differential Omega, although transient effects are potentially quite important wherever high accuracy must be maintained continuously during some period, such as during a non-precision approach.

There are several plausible reasons for the large overshoot that was observed, including lags or errors in the aiding inputs (true airspeed and heading), and lags or errors in the tracking loops or navigation filter of the Omega receiver. The limited data do not permit a definitive analysis of the reason for the position overshoots following maneuvers. However, since predicted behavior [6] contained much smaller overshoots than were observed, it is likely that the observed overshoots resulted from a system malfunction rather than from a design characteristic.

Data-link range was observed to vary from 44 NM to 198 NM, depending on the level of radio noise and the orientation of the aircraft antenna. The small sample size does not permit a probability of successful signal reception to be assigned to any range, although it is obvious that in most of the cases observed, the effective range of the data link was less than will be required by an operational system. In order that data-link range not be the limiting factor in any practical application of Differential Omega, it seems that reliable data-link range should be at least 200 NM at all times, which is a factor of nearly five over the smallest range limit observed during the tests.

Data-link range can certainly be improved over that observed. Available techniques for improving data-link range include increasing transmitter power, increasing modulation level on the side-tone, decreasing the link data rate, and providing software (such as error-correcting codes) that is more tolerant of bit errors in the data.

Probably the most powerful and cost-effective technique for increasing the range of the data link is to reduce the link data rate. The present system sends a complete, 400-bit error message every 10 seconds. The data are sent at 125 baud so that transmission of a complete message requires 3.2 seconds.

Studies [9] and observations of Omega phases during these tests both suggest that update periods of up to five minutes are adequate for accurate performance of Differential Omega. If the data link were reconfigured to provide one update per 100 seconds at 4.0 baud, the required bandwidth of the link could decrease by a factor of 31.25 yielding a range multiplication of 5.6. If we take 44 NM as representative of the existing reliable data-link range, then the suggested change would provide a reliable data-link range of greater than 245 NM with no significant sacrifice in system performance. Furthermore, baseband circuits supporting a 4-Hz data stream can be designed to operate at subcarrier frequencies as low as 30 Hz. Systems can be designed that will simultaneously accommodate a 30-Hz telemetry signal and a normal audio (voice) signal [10]. The implication of this fact is that if the Differential Omega data link were reconfigured as suggested, then it would no longer be necessary to disable weather broadcasts from a beacon transmitter when the beacon is to be used in support of Differential Omega, thus removing one of the minor irritations experienced during the flight tests.

System reliability is related primarily to outages caused by the loss or malfunction of any of the system components. During the October 1980 tests, the Deadhorse monitor experienced an outage of several hours duration and Transmitter H (Japan) was off the air for several weeks. During the February 1981 tests, the Anchorage monitor experienced an outage of several hours. Both monitor outages caused a complete loss of Differential Omega during test flights.

Reliability can be increased through improved design, improved procedures and system redundancy. The Deadhorse outage resulted from the accidental cutting of the cable connecting the monitor receiver and the beacon transmitter, about 100 meters away. This type of problem can be mitigated either by colocating the receiver and transmitter or by providing better protection for connecting cables. The Anchorage outage resulted from a transient in municipal power that caused the program in the receiver processor to crash, with no permanent damage. In any permanent system, it should not be difficult to provide isolation between line power and processor software.

There is always, in any system, the possibility of failures that have not been anticipated as well as the requirement to deactivate a system for routine maintenance. Offsetting this problem may require a geographical distribution of monitors so as to provide a redundancy of data links. Swanson [4] has pointed out that a redundant distribution of monitor stations also permits increased sophistication in the differential correction algorithm that will decrease range decorrelation error significantly. Monitor redundancy did not exist during the Alaska flight tests so there was no opportunity to evaluate the benefits of such redundancy. Nevertheless, in any future evaluation of Differential Omega, consideration should be given to relocating one or more of the monitors to provide redundant coverage over some test area.

The observed performance of the present system provides some insight into the achievable performance of Differential Omega navigation in Alaska. The most fundamental limitation to navigational accuracy of Differential Omega appears to be range decorrelation error, at least at longer ranges. At short ranges from the monitor, steady-state navigational errors can be reduced to a level no greater than about 0.25 NM.

Convergence time of the Tracor 7620 following initialization seems inconveniently long for use in many general aviation applications. It should not be necessary for an aircraft to start the engine(s) twenty minutes before every takeoff merely to assure accurate navigation. It may be appropriate to design into any operational avionics a special standby mode that enables the system to track signals with a minimum power drain. In addition, any operational system should include a fail safe design that will insulate the receiver/processor from brief outages or transients in aircraft power.

The observed transient response of the Tracor 7620 following aircraft maneuvers was not satisfactory. The FAA recognizes the inherent problem of overshoot in area navigation systems [11] and suggests that pilots anticipate course changes by one mile for each 100 knots true airspeed in order to mitigate such effects. It is clear, however, that even using such procedures, the observed accuracy of Differential Omega navigation under the circumstances of the February flight tests would have degraded for a short time following aircraft turns. Obviously, transient behavior of Differential Omega is an important consideration for any operational system.

V. CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this project has been the development and evaluation of a Differential Omega system. Most of the field testing has taken place in Alaska and some of the results that have been achieved are indicative of the particular nature of the Alaskan environment.

Taken as a whole, the flight test results do not reflect the performance of a fully developed, operational Differential Omega system. However, from the results that were achieved and from an understanding of the nature of the imperfections that were observed in the system performance, one can deduce the potential performance of Differential Omega for airborne navigation in Alaska and can establish the major design requirements for an operational system.

The results suggest that Differential Omega can provide reliable operation and improved performance for data-link ranges at least as great as 200 NM. At very small data-link ranges, accuracies approaching 0.25 NM 2-DRMS are achievable. Accuracy should degrade slowly with increasing range.

The results also suggest that Differential Omega, when properly implemented, can meet requirements for terminal operations and non-precision approach as well as for enroute navigation.

The flight tests of the prototype system have yielded valuable information on the major characteristics and design parmeters that will be required by a fully operational system. The required characteristics that have been identified can be summarized as follows:

(1) Monitor stations should be geographically distributed so as to provide redundancy for all potential users. The monitors themselves should be designed to be highly immune to transients or outages in line power.

(2) Differential corrections should be updated about once every 100 seconds. Data rate need be no greater than about 4 Hz. A modulation method should be adopted such that telemetry and voice can be broadcast simultaneously from the DF beacon transmitter.

(3) Monitor stations in Alaska should process differential corrections only for Omega signals from A, C, D and H and at frequencies of 10.2 kHz and 13.6 kHz.

(4) Transient performance requirements for area navigation systems have not been clearly specified by the FAA. Nevertheless, the transient response of the Omega receiver used in the Alaska tests was clearly excessive for nonprecision approach. Since overshoot is an unavoidable characteristic of most area navigation systems, acceptable levels of transient performance should be specified in order to establish design criteria clearly for future systems.

(5) Airborne Omega receivers should be designed to include a "standby" mode in which Omega signals will be tracked and processed, and navigation solutions computed at a minimum power drain.

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APPENDIX A

DIFFERENTIAL CORRECTION MESSAGE FORMAT

Length 40 bytes
Information 7 bit ASCII, even parity

Byte #	Data	Byte #	Data
1	ASCII S	21	MS Part Correction Station 3 13.6
2	ASCII 1	22	LS Part Correction Station 3 13.6
3	ASCII 1	23	MS Part Correction Station 4 13.6
4	ASCII 2	24	LS Part Correction Station 4 13.6
5	ASCII 0	25	MS Part Correction Station 1 11.33
6	ASCII 0	26	LS Part Correction Station 1 11.33
7	ASCII 0	27	M Part Correction Station 2 11.33
8	Station Identifier ASCII 1-3	28	LS Part Correction Station 2 11.33
9	MS Part Correction Station 1 10.2	29	M Part Correction Station 3 11.33
10	LS Part Correction Station 1 10.2	30	LS Part Correction Station 3 11.33
11	MS Part Correction Station 2 10.2	31	MS Part Correction Station 4 11.33
12	LS Part Correction Station 2 10.2	32	LS Part Correction Station 4 11.33
13	M Part Correction Station 3 10.2	33	Usable Stations E-H 10.2
14	LS Part Correction Station 3 10.2	34	Usable Stations A-D 10.2
15	MS Part Correction Station 4 10.2	35	Usable Stations E-H 13.6
16	LS Part Correction Station 4 10.2	36	Usable Stations A-D 13.6
17	MS Part Correction Station 1 13.6	37	Usable Stations E-H 11.33
18	LS Part Correction Station 1 13.6	38	Usable Stations A-D 11.33
19	MS Part Correction Station 2 13.6	39	Checksum
20	LS Part Correction Station 2 13.6	40	Checksum

APPENDIX B

SYSTEM INTEGRATOR FOR OMEGA NAVIGATION SYSTEM

The System Integrator for the Omega Navigation System receives a demodulated subcarrier from the ADF receiver, detects the data, selects the appropriate data for the system and sends the data to the Omega System. The software functions required in performing the system function are:

- convert the input subcarrier to digital samples
- track the phase of the subcarrier
- detect the presence of the subcarrier
- detect the timing of the digital modulation on the subcarrier (bit sync)
- detect the data
- detect the data header
- select and reformat the data for the Omega system
- output the data to the Omega System

An executive program is required to control the subfunctions. The executive is initialized every 8 ms except when preparing an output message. The executive programming is interrupted every 1 ms by the interrupt program to input and store a data sample and to output data. The samples are processed every 8 ms by the executive program.

The operating modes for the system are defined in Table 1. Communications between the software modules take place with the control codes. Table 2 lists the counters used by the modules. Figure 1 shows the executive software.

Table 1 Operating Modes

MODE	CONTROL CODE				OUTPUT		MODE TRANSITIONS					
	HOLD		BIT SYNC	SUBCARRIER	HEADER DATA	HOLD DATA	SUBCARRIER	SUBCARRIER	BIT SYNC	BIT SYNC	HEADER	HOLD TIMER
1	0	0	0	0	x		2	-	-	-	-	-
2	0	0	0	1	x		-	1	3	-	-	-
3	0	0	1	1	x		-	1	-	2	-	-
4				1								
5	1	0	0	0	x	x	5	-	-	-	-	1
6	1	0	0	1	x	x	-	4	6	-	-	1
7	1	0	1	1	x	x	-	4	-	5	-	1

Mode 3 is normal operating mode

Modes 1-2 are acquisition modes

Modes 4-6 are reacquisition after message has been received

Mode 1 Subcarrier is not detected; data have not been received recently.

Mode 2 Subcarrier has been detected; bit synch has not been established; data have not been received recently.

Mode 3 Normal operating mode

Mode 4 Same as with 1 with reacquisition

Mode 5 Same as with 2 with reacquisition

Mode 6 Same as with 3 with reacquisition

Table 2

COUNTER	INCREMENT	RANGE	MODULE	USAGE
Interrupt Input Counter	1 Interrupt	0-8	Interrupt	Used to reinitialize executive every eighth interrupt
Interrupt Output Counter	1 Interrupt	0-10	Interrupt	Used to output a bit every tenth interrupt
Output Bit Counter	1 Bit	0-8	Interrupt	Counts bits to be output
Output Bit Counter	1 Word	7F-FC	Interrupt	Contains current word to be output
Signal Detect Counter	8 Millisecond	0-12	Subcarrier Detect	Used to count off 0.1 sec
Bit Counter	1 Bit	0-9	Bit Processing Executive	Used to mask off input or parity
Character	1 Character	3F-67	Bit Processing, Character, Processing Executive	Used to keep track of current character
Hold Timer	8 Millisecond	0-8 Min	Hold Processing	Used to count off eight minutes since last message was received

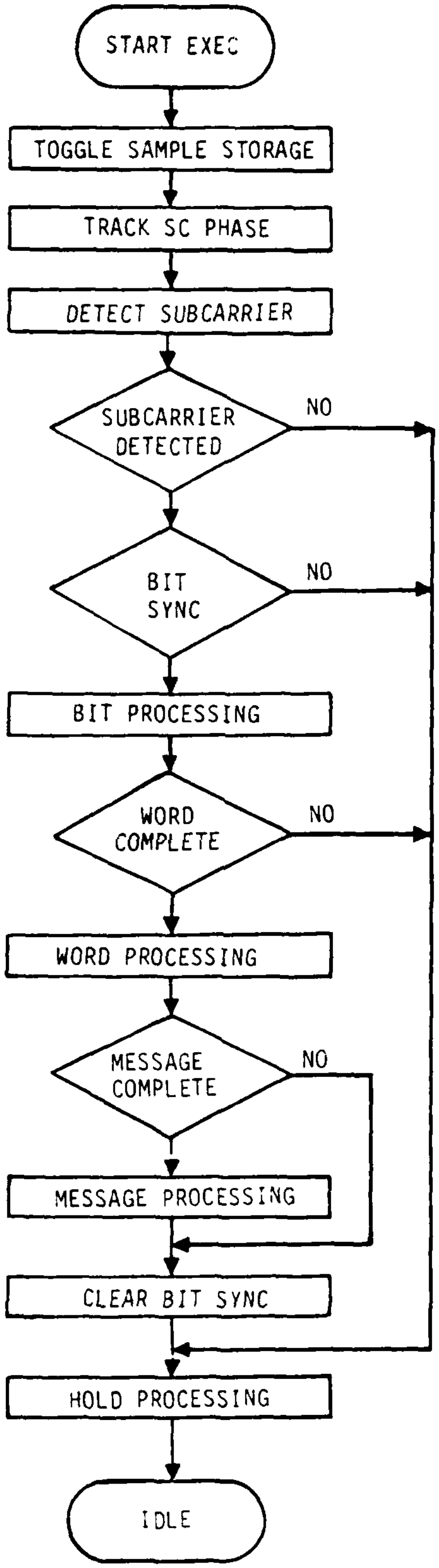


FIGURE 1. EXECUTIVE.

SUBCARRIER PHASE TRACK

A combination of hardware and software is used to adjust the sampler to take alternate samples on the peaks and zero crossings of the subcarrier. The hardware portion is shown in Figure 2 and the software flow diagram in Figures 2b and 2c. An analog equivalent of the phase tracking system is shown in Figure 3.

The sampling process provides alternate samples three-quarters and one and one-quarter cycles apart (see Figure 4). The change of sample timing is accomplished by adjusting the count of a preset counter (see Figure 5).

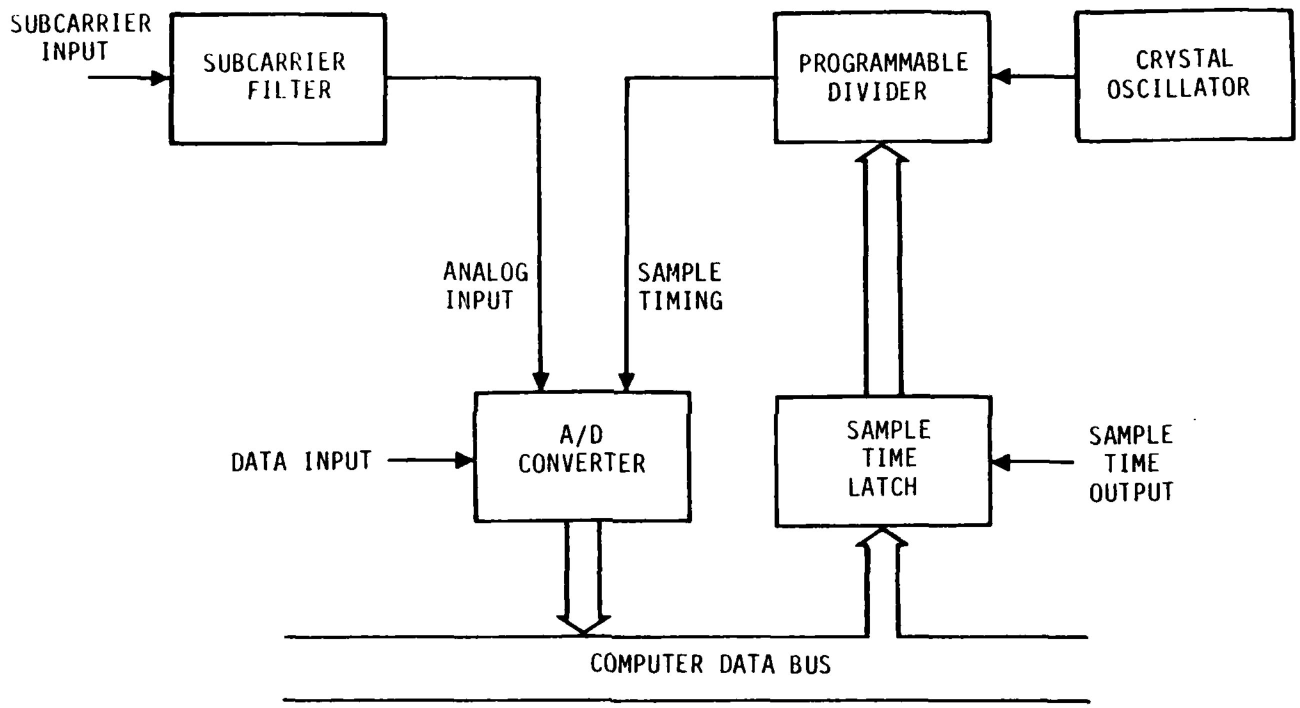


FIGURE 2. SUBCARRIER PHASE TRACK HARDWARE.

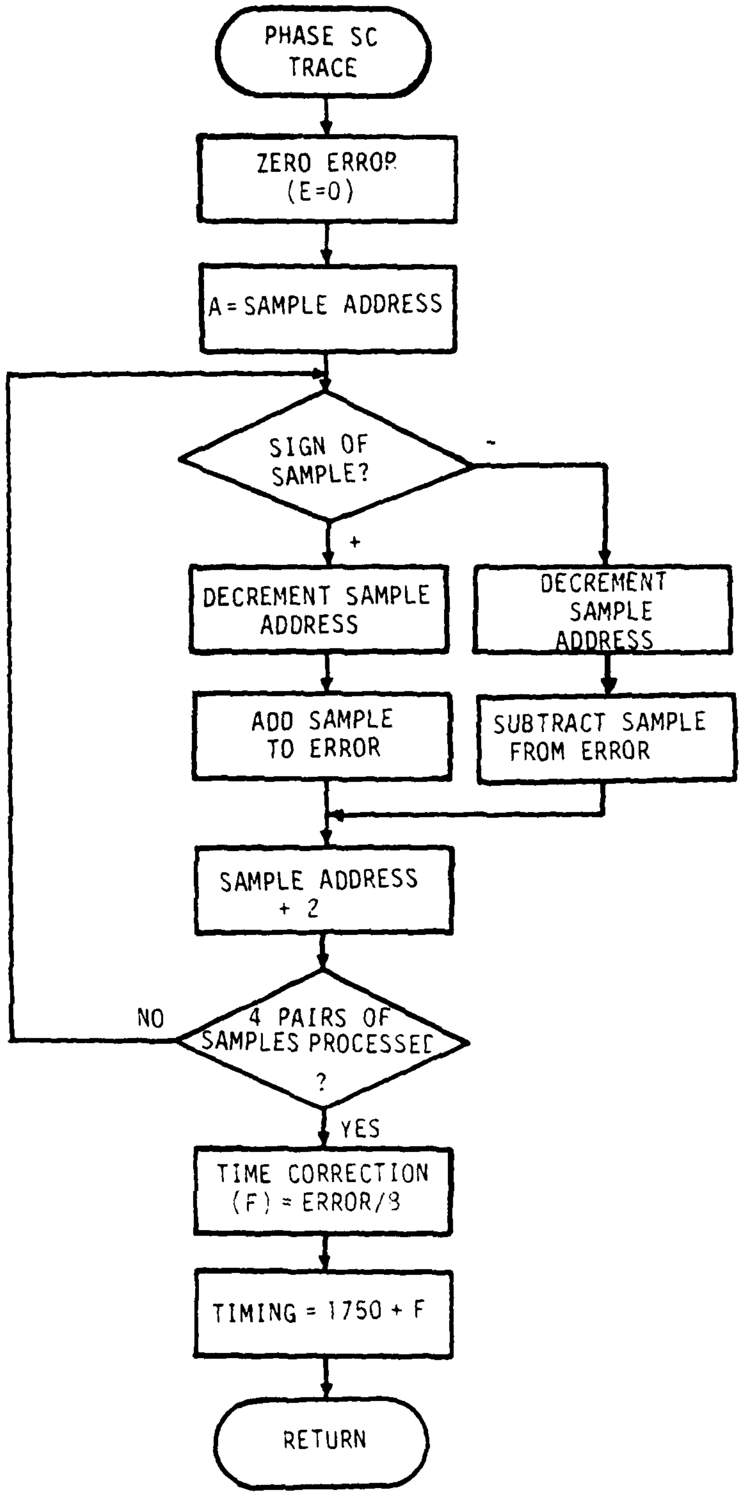


FIGURE 2B. SUBCARRIER PHASE TRACK.

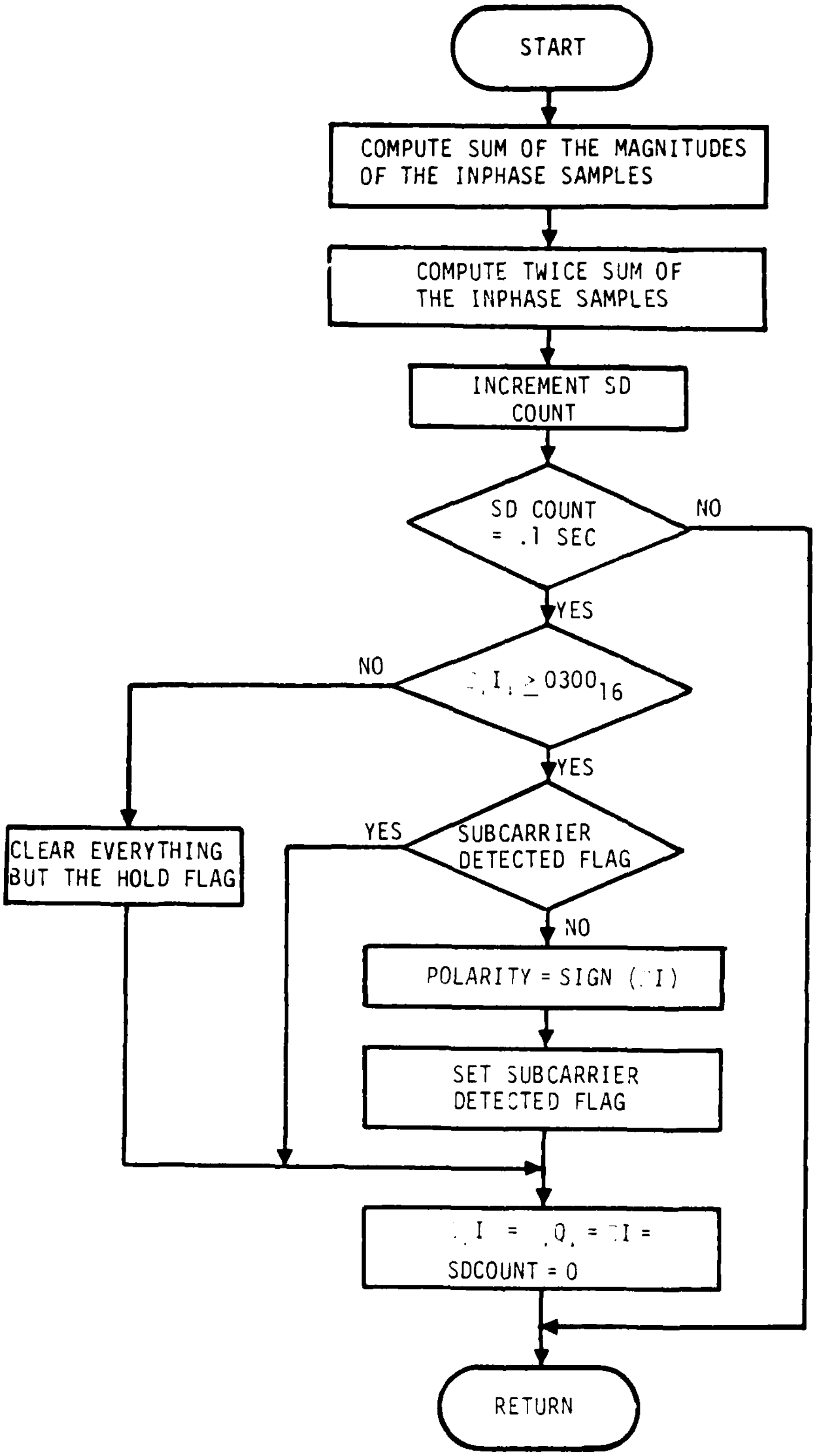


FIGURE 2C. DETECT SUBCARRIER

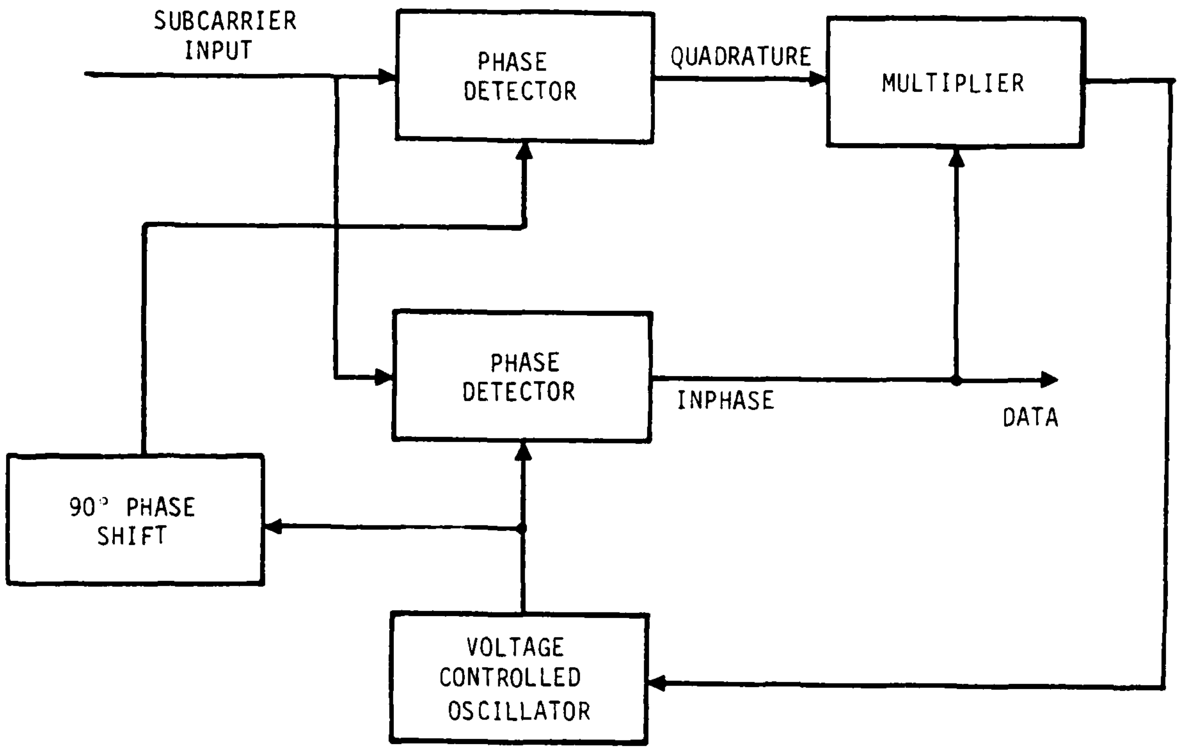
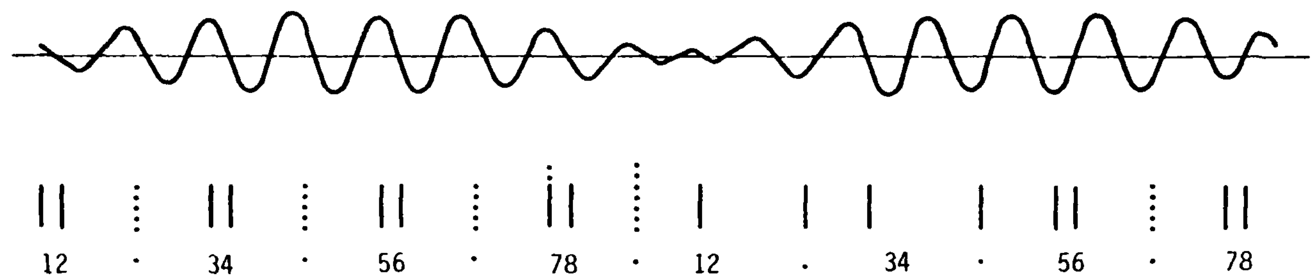


FIGURE 3. ANALOG EQUIVALENT OR PHASE TRACKING SYSTEM.

SUBCARRIER DETECTION

The presence of the subcarrier is detected by comparing the amplitude of the in-phase component of the signal to the quadrature component. Since the carrier is phase reversal modulated, the magnitude of the samples must be evaluated.

The magnitude of in-phase and quadrature samples is integrated for .4 seconds. At the end of the time, a signal is considered to be present if the in-phase sum is twice as large as the quadrature sum.



INTERRUPT	OUTPUT TIME
1	$1250 + (F \times 8)_T$
2	750
3	1250
4	750
5	1250
6	750
7	1250
8	750

FIGURE 4. SAMPLE TIMING

TIMING CONTROL

1. Divide number of μsec between samples by two.

2. Convert the results into three BCD digits - a, b, c, and a remainder r. r may be 1 or 0.

3. Output 1 is two BCD digits - b, c.

4. Output s is the third BCD digit and the remainder rxxxx, a.

Example:

Output: 1751 μsec

$$2 \overline{)1751} \quad 875 \qquad r=1$$

Output 4 = remainder is most significant bit 8 8
1000 1000

Output 1 = 75
0111 0101

Test program used to check timing.

ADD	INST		COMMENT
00	71	DIS	Disable Interrupt
01	00		X = D P = 0
02	61	OUR1	Output 1 75
03	75		
04	65	OUTS	Outputs 88
05	88		
06	00	IDL	Idle

Figure 5

BIT SYNC (PART OF INTERRUPT)

The analog equivalent of the bit sync process is shown in Figure 6. The in-phase samples are amplitude samples of the filtered data wave form. The filtering is provided by the hardware subcarrier band pass filter. The filtered wave form is rectified and multiplied by double the bit rate reference. The resulting wave form has a zero average value when the reference phase has a zero crossing at the bit transition time and a positive or negative average value when displaced from this timing. The average value of the reference times the magnitude of the in-phase samples is examined to determine if a discrete change in timing is required. The software flow diagram is shown in Figure 6b.

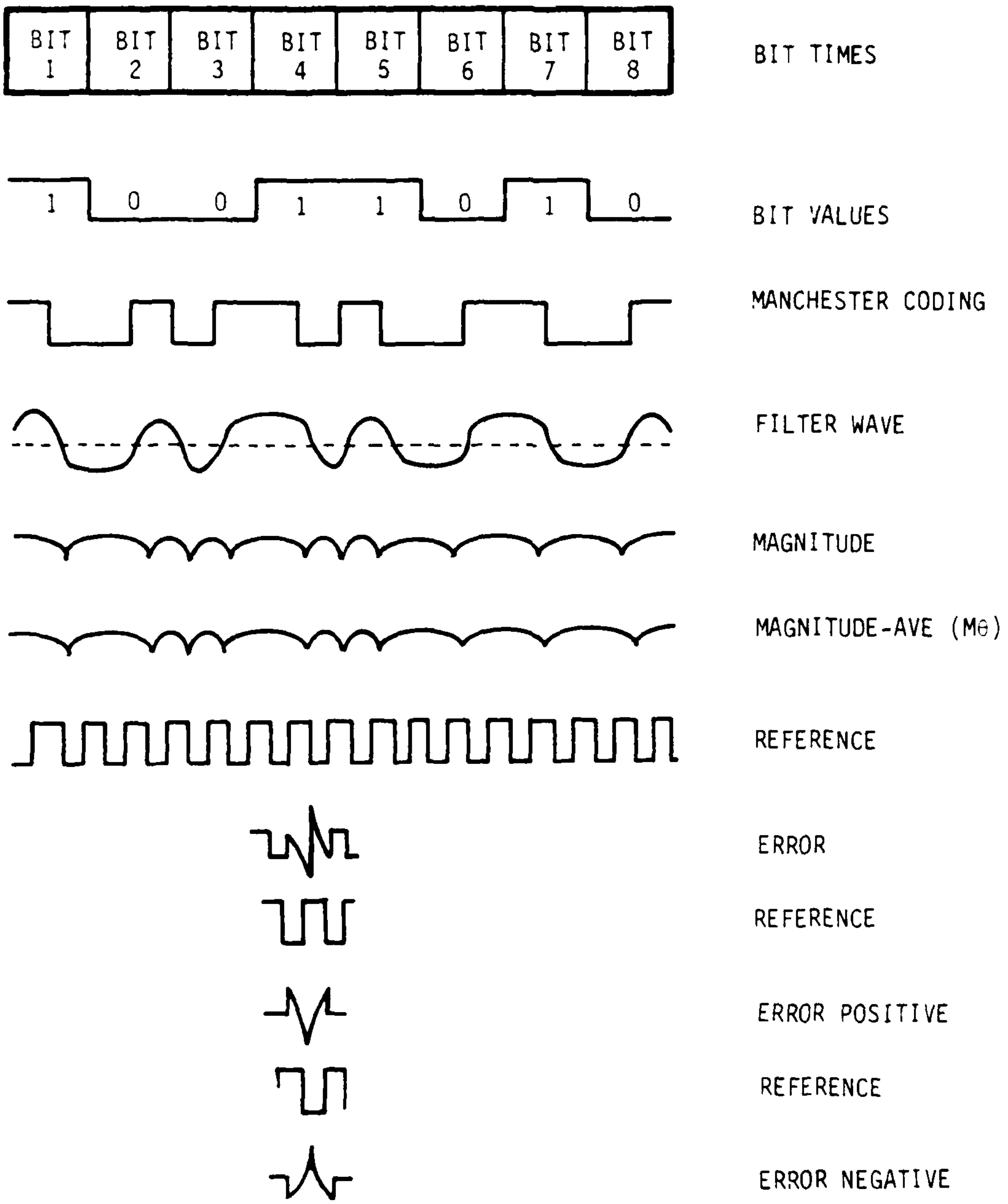

BIT 1
BIT 2
BIT 3
BIT 4
BIT 5
BIT 6
BIT 7
BIT 8
BIT TIMES
1 0 0 1 1 0 1 0
BIT VALUES
MANCHESTER CODING
FILTER WAVE
MAGNITUDE
MAGNITUDE-AVE (Mθ)
REFERENCE
ERROR
REFERENCE
ERROR POSITIVE
REFERENCE
ERROR NEGATIVE

FIGURE 6.

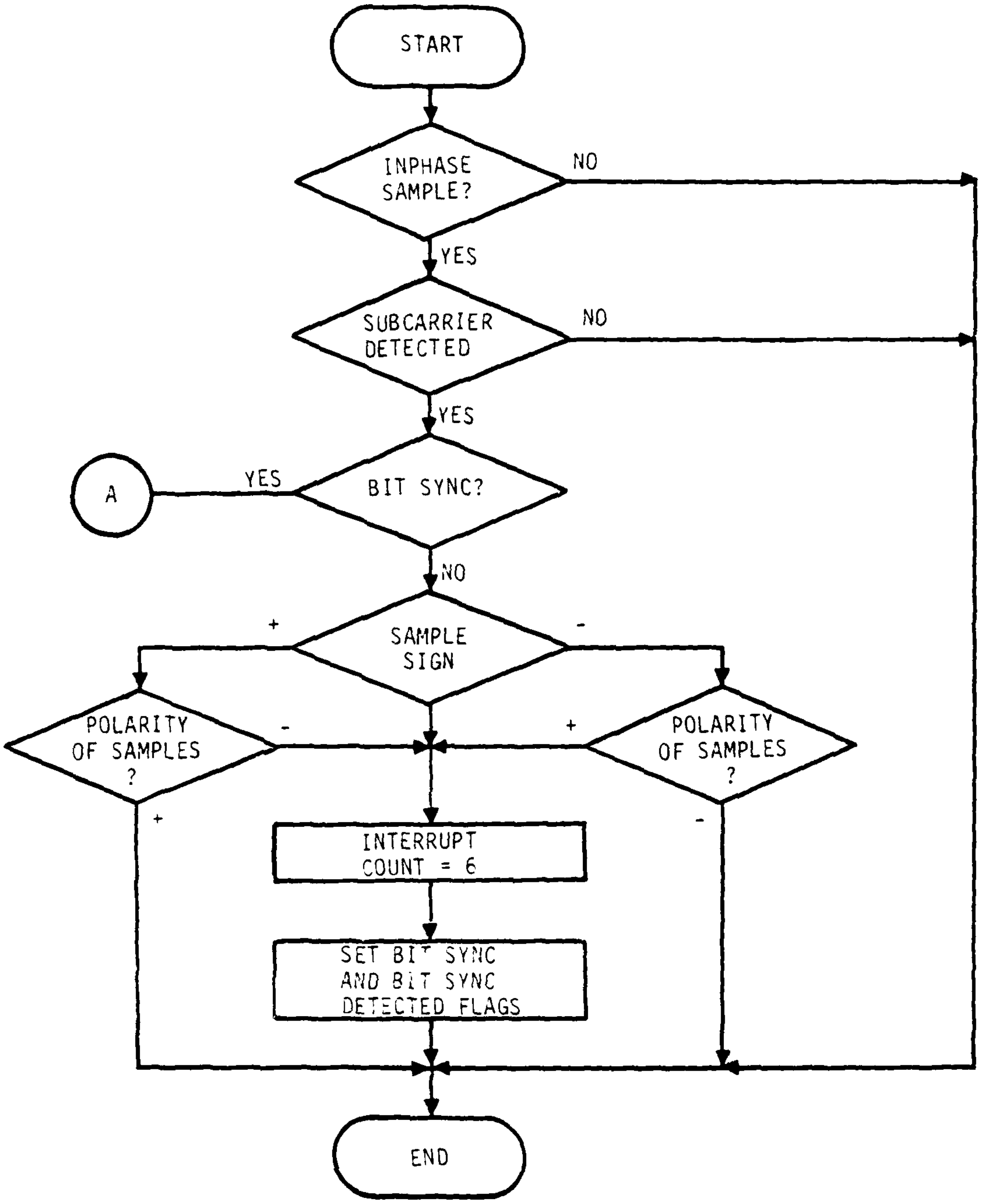


FIGURE 6B. BIT SYNC

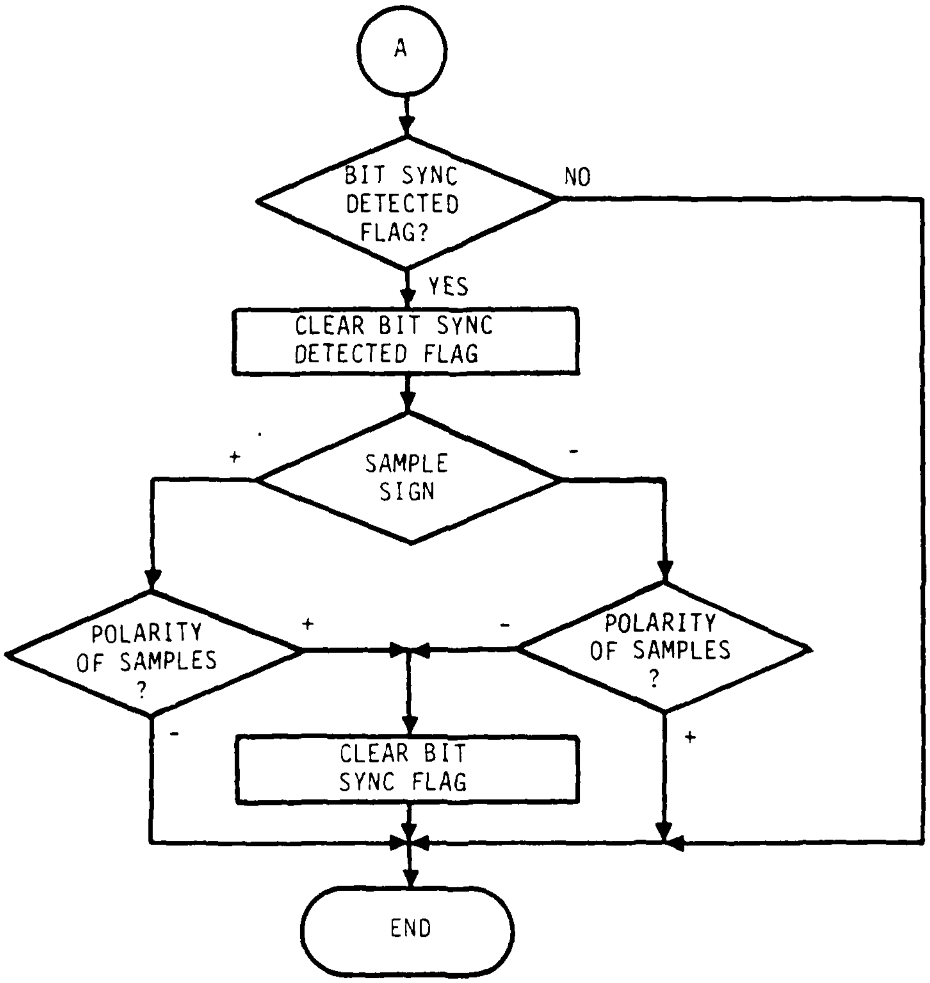


FIGURE 6B. Continued

BIT PROCESSING

Each group of 8 samples represents 1 bit of 1 character of the input message. By comparing the sign of the last sample received and polarity for this group of samples, this module determines the value of the bit. If the sign of the sample and polarity are the same, then the bit is a 1; if they are different, the bit is a 0. The routine after determining the value of the bit stores it in its proper place in the input message. The software flow diagram is shown in Figure 7.

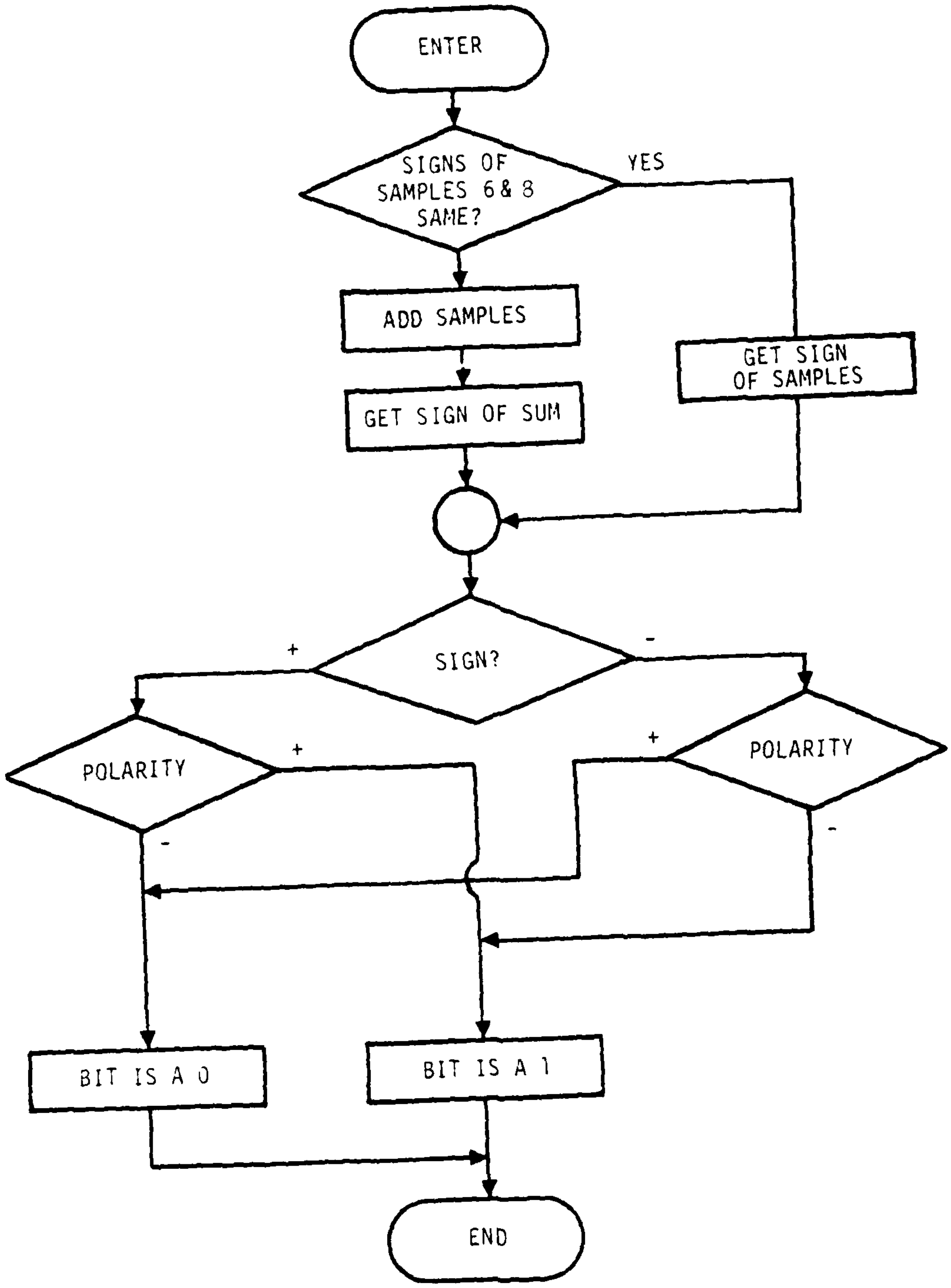


FIGURE 7. BIT PROCESSING.

CHARACTER PROCESSING

In order to identify an input message properly, the first two characters of the message must be checked to see if they are ASCII S1. If the first two characters are not S1 then the first one is discarded and the program will continue checking for S1. When S1 is found, the message processing flag is set. In addition, each character is checked for a parity error. If one is found, then the parity error flag is set. See Figure 8 for the software flow diagram.

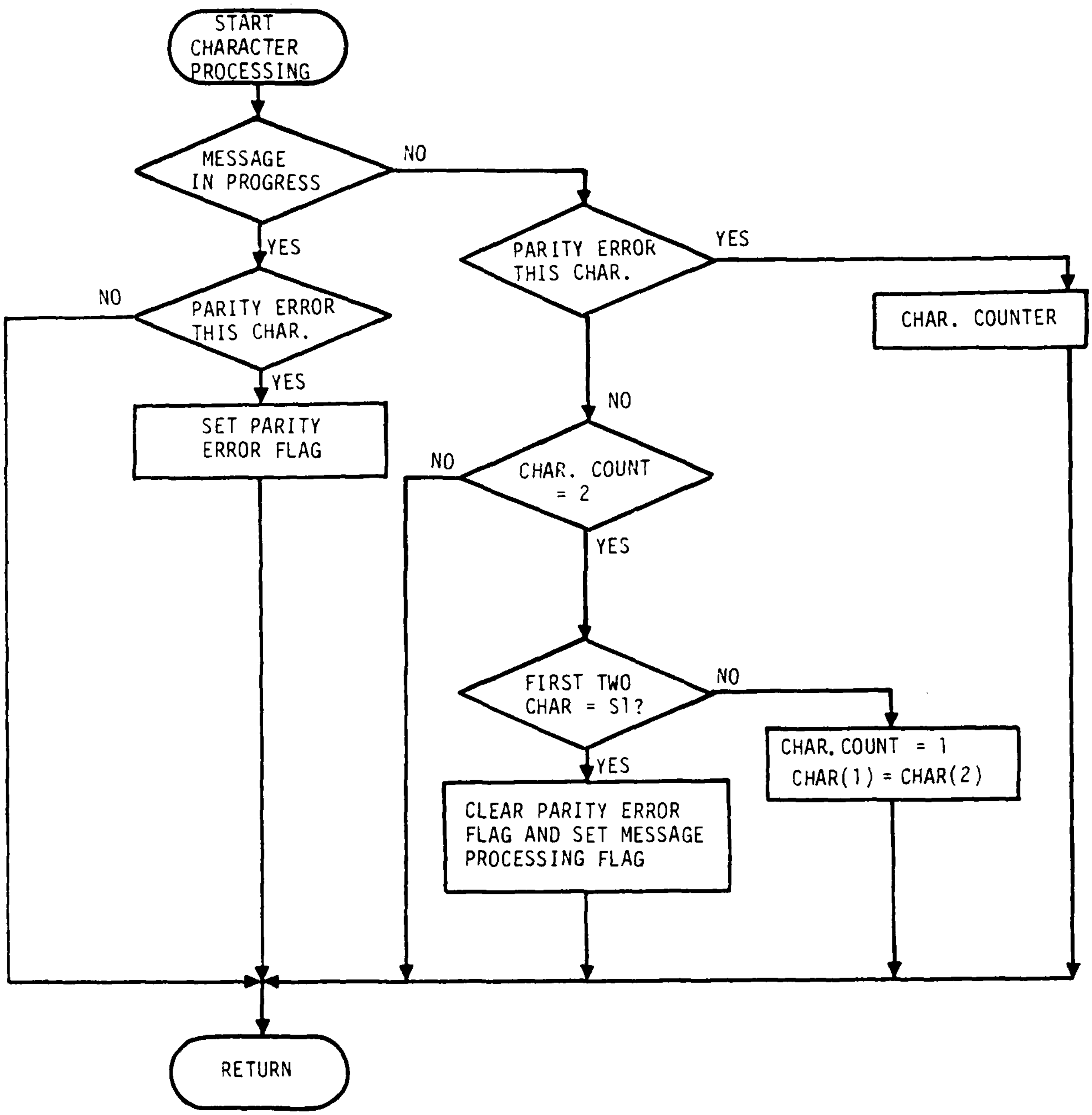


FIGURE 8. CHARACTER PROCESSING

MESSAGE PROCESSING

This module takes the 40-character input message, checks the check sum, converts each character from ASCII to HEX, finds the usable stations and puts the usable stations and their respective phase correction in the output message. Upon completion of message processing, the message ready flag is set and the hold timer is initialized. If a parity error were found during character processing or the check sum were in error, then the message processing flags are cleared. the format of the input message is shown in Table 3. The phase corrections (characters 8-31) are the ASCII equivalent of the HEX digits of the signed binary numbers representing the phase corrections. The usable stations (characters 32-37) are the ASCII equivalent of the HEX digit determined by assigning a 1 to each usable station. Characters 32, 34, 36 indicate which of stations A, B, C, and D are usable and characters 33, 35, 37 indicate which of stations E, F, G and H are usable. The check sum is the 1's complement of the sum of the HEX bytes derived from characters 2-37. It is transmitted in ASCII also.

The format of the output message is shown in Table 4. The usable stations are represented as a 16-bit word with the 8 least significant bits representing stations A-H, respectively. A 1 in the bit position for a station means it is usable. The phase corrections are signed 16-bit twos complement integers with a range of 255 x lanes x 10^{-2} to -255 x lanes x 10^{-2}. Setting the least significant bit of word 37 signifies that the message is ready. The check sum word 38 is the 1's complement of the sum of words 2-37. Figure 9 shows the message processing software flow.

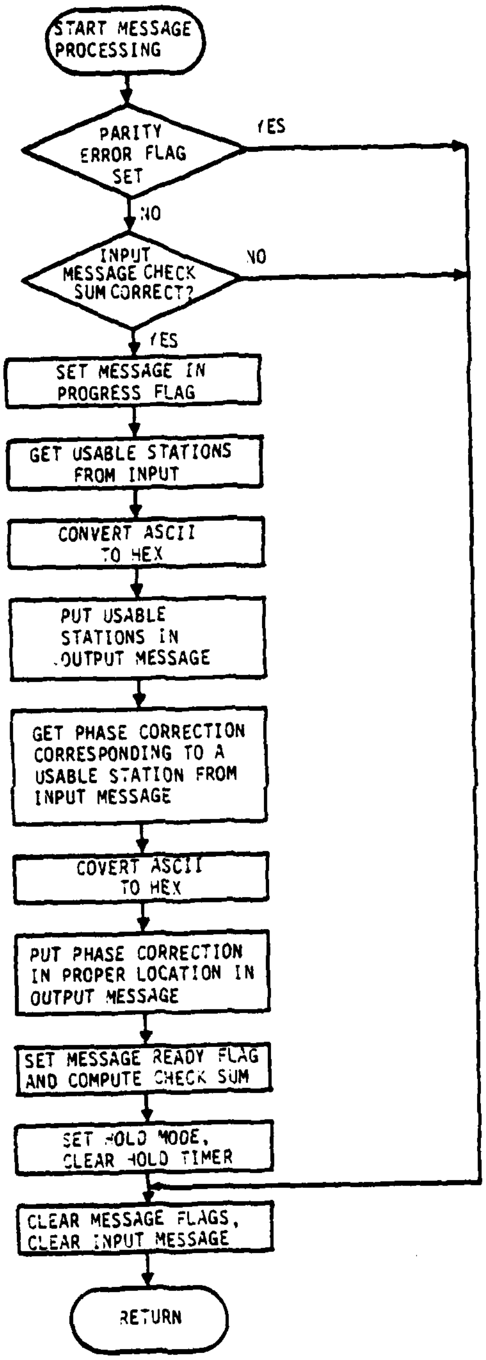


FIGURE 7. MESSAGE PROCESSING.

Table 3

CHARACTER	FUNCTION
0,1	S1 Header
2,3	Byte Count
4,5	Identification
6,7	Identification
8,9	Station 1 10.2 Phase
10,11	Station 2 10.2 Phase
12,13	Station 3 10.2 Phase
14,15	Station 4 10.2 Phase
16,17	Station 1 13.6 Phase
18,19	Station 2 13.6 Phase
20,21	Station 3 13.6 Phase
22,23	Station 4 13.6 Phase
24,25	Station 1 11-1/3 Phase
26,27	Station 2 11-1/3 Phase
28,29	Station 3 11-1/3 Phase
30,31	Station 4 11-1/3 Phase
32,33	10.2 Stations
34,35	13.6 Stations
36,37	11-1/3 Stations
38,39	Check Sum

Each two bytes of the Canadian message are reformatted into one byte to decode the message. For instance, if words 9 and 10 were 46 (ASCII for F) and 41 (ASCII for A), respectively, then the correction to be applied to the first usable station of frequency 10.2 would be hex FA.

Also, if words 33,34 were 34 (ASCII for 4) and 45 (ASCII for E) then the usable stations would be B, C, D, G,

	H	G	F	E	D	C	B	A
4E = 0	0	1	0	0	1	1	1	0

The checksum is the 2-byte ASCII equivalent of the 1-byte number which when added to the sum of the other bytes, excluding the header, will equal FF.

For instance, if the sum of bytes 2-38 is 83, then byte 39 would be 37 (ASCII for 7) and byte 40 would be 43 (ASCII for C).

The listing for the test generator program has a table of numbers, their ASCII equivalent and their equivalent required by the output program. The easiest way to compute the checksum is with a hex calculator if you have one.

Table 4

Data Interface Format

WORD	DESCRIPTION				SCHEDULING
0	0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1			HEADER	OPEN CIRCUIT IS "1", CURRENT SINK IS "0"
1	0 0 0 0 0 0 0 0 A B C D E F G H			10.2 USABLE	"1" IS STATION USABLE
2	0 0 0 0 0 0 0 0 A B C D E F G H			13.6 USABLE	"1" IS STATION USABLE
3	0 0 0 0 0 0 0 0 A B C D E F G H			11 1/3 USABLE	"1" IS STATION USABLE
4	0 0 0 0 0 0 0 0 A B C D E F G H			11.05 USABLE	"1" IS STATION USABLE
5	STATION A	10.2	KH_z	PHASE CORRECTIONS	
6	STATION B	10.2	KH_z	PHASE CORRECTIONS	
7	STATION C	10.2	KH_z	PHASE CORRECTIONS	
8	STATION D	10.2	KH_z	PHASE CORRECTIONS	
9	STATION E	10.2	KH_z	PHASE CORRECTIONS	
10	STATION F	10.2	KH_z	PHASE CORRECTIONS	
11	STATION G	10.2	KH_z	PHASE CORRECTIONS	
12	STATION H	10.2	KH_z	PHASE CORRECTIONS	
13	STATION A	13.6	KH_z	PHASE CORRECTIONS	
14	STATION B	3.6	KH_z	PHASE CORRECTIONS	
15	STATION C	13.6	KH_z	PHASE CORRECTIONS	
16	STATION D	13.6	KH_z	PHASE CORRECTIONS	
17	STATION E	13.6	KH_z	PHASE CORRECTIONS	
18	STATION F	13.6	KH_z	PHASE CORRECTIONS	
19	STATION G	13.6	KH_z	PHASE CORRECTIONS	
20	STATION H	13.6	KH_z	PHASE CORRECTIONS	
21	STATION A	11.1-1/3	KH_z	PHASE CORRECTIONS	

Table 4

Data Interface Format

(Cont'd.)

WORD	DESCRIPTION				SCHEDULING
22	STATION B	11.1-1/3	KH_z	PHASE CORRECTION	
23	STATION C	11.1-1/3	KH_z	PHASE CORRECTION	
24	STATION D	11.1-1/3	KH_z	PHASE CORRECTION	
25	STATION E	11.1-1/3	KH_z	PHASE CORRECTION	
26	STATION F	11.1-1/3	KH_z	PHASE CORRECTION	
27	STATION G	11.1-1/3	KH_z	PHASE CORRECTION	
28	STATION H	11.1-1/3	KH_z	PHASE CORRECTION	
29	STATION A	11.05	KH_z	PHASE CORRECTION	
30	STATION B	11.05	KH_z	PHASE CORRECTION	LANES x $1\bar{0}^2$
31	STATION C	11.05	KH_z	PHASE CORRECTION	
32	STATION D	11.05	KH_z	PHASE CORRECTION	
33	STATION E	11.05	KH_z	PHASE CORRECTION	
34	STATION F	11.05	KH_z	PHASE CORRECTION	
35	STATION G	11.05	KH_z	PHASE CORRECTION	
36	STATION H	11.05	KH_z	PHASE CORRECTION	
37	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 M			MODE	M-1 DIFFERENTIAL OMEGA MODE M=0 SWC MODE
38	CHECK SUM				SUM OF WORDS 1-37
39	SPARE				
40	"				
41	"				
42	"				
43	"				

Data Interface Format
(Cont'd.)

WORD	DESCRIPTION	SCHEDULING
44	SPARE	
45	"	
46	"	
47	"	
48	"	
49	"	
50	"	
51	"	
52	"	
53	"	
54	"	
55	"	
56	"	
57	"	
58	"	
59	"	
60	"	
61	"	
62	"	
63	0 Bit ½ WORD	

Tracor 7620 Omega Navigator:

This receiver has been modified to accept the differential signal and process it to correct the Omega position information. Information on operation of this equipment may be found in Omega Navigation Equipment, Operation and Maintenance Instructions, OM-401-235-1, Tracor, and Differential Omega Field Test Operator's Checklist, SCI. Diagnostic messages are stored in several memory locations within the 7620. These may be used to determine probable sources of difficulty in troubleshooting the differential Omega system. The memory locations may be accessed using a "99" test (Direct Memory Access) described in the maintenance instructions. Several useful memory locations are given in Table 5 along with the significance of their contents.

Table 5: 7620 Diagnostic Messages

The memory locations and messages below are accessed in a "99" test and are given in octal notation unless otherwise specified.

Location	Significance of Contents
3115	Sync confidence. Computer resets it to 200. Increases 20 with good header, decreases 30 for bad header, increases 30 for good check-sum, decreases 40 for bad checksum. Maximum is 377.
3113	Bit sync confidence. Starts at 100.
3104	If a 010 is stored here the 7620 initiates resync and ignores checksum errors.
3202	Differential stations OK (information gotten from integrator message). A "1" in the station's position indicates a useable station e.g. A B C D E F G H - 261_8 1 0 1 1 0 0 0 1 A 261 indicates that stations A,C,D and H are useable.
0277	Differential Deselect. This shows the stations being used by the 7620.

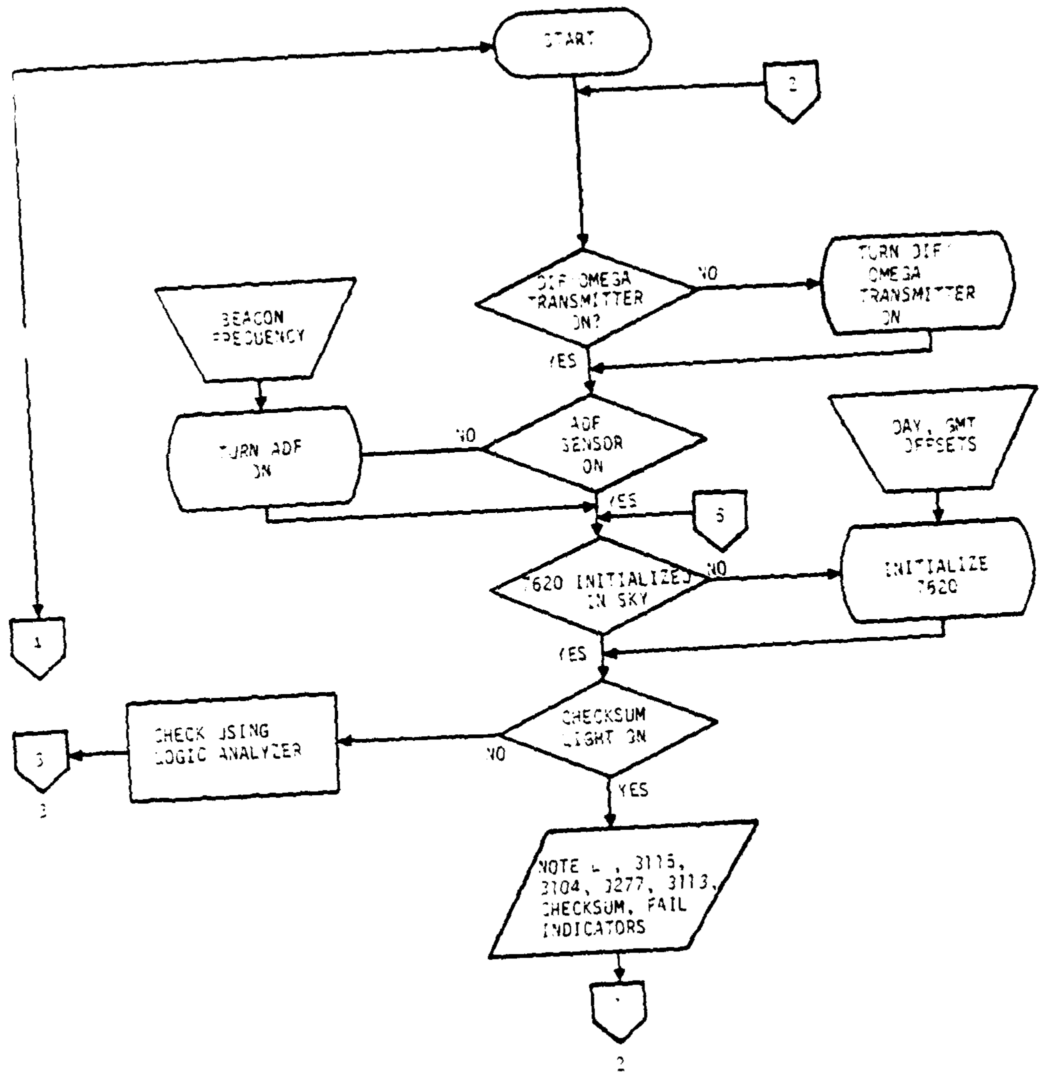
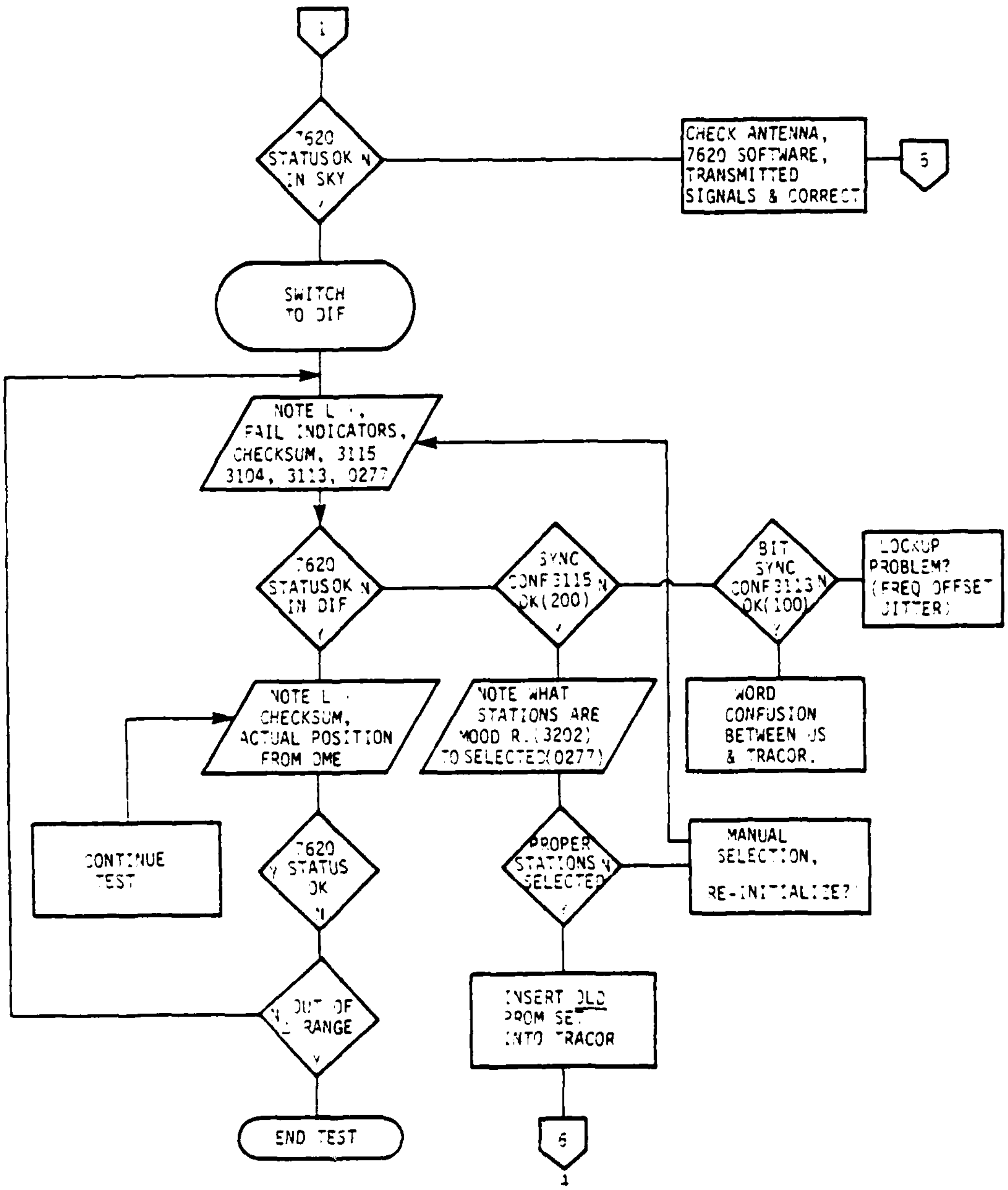
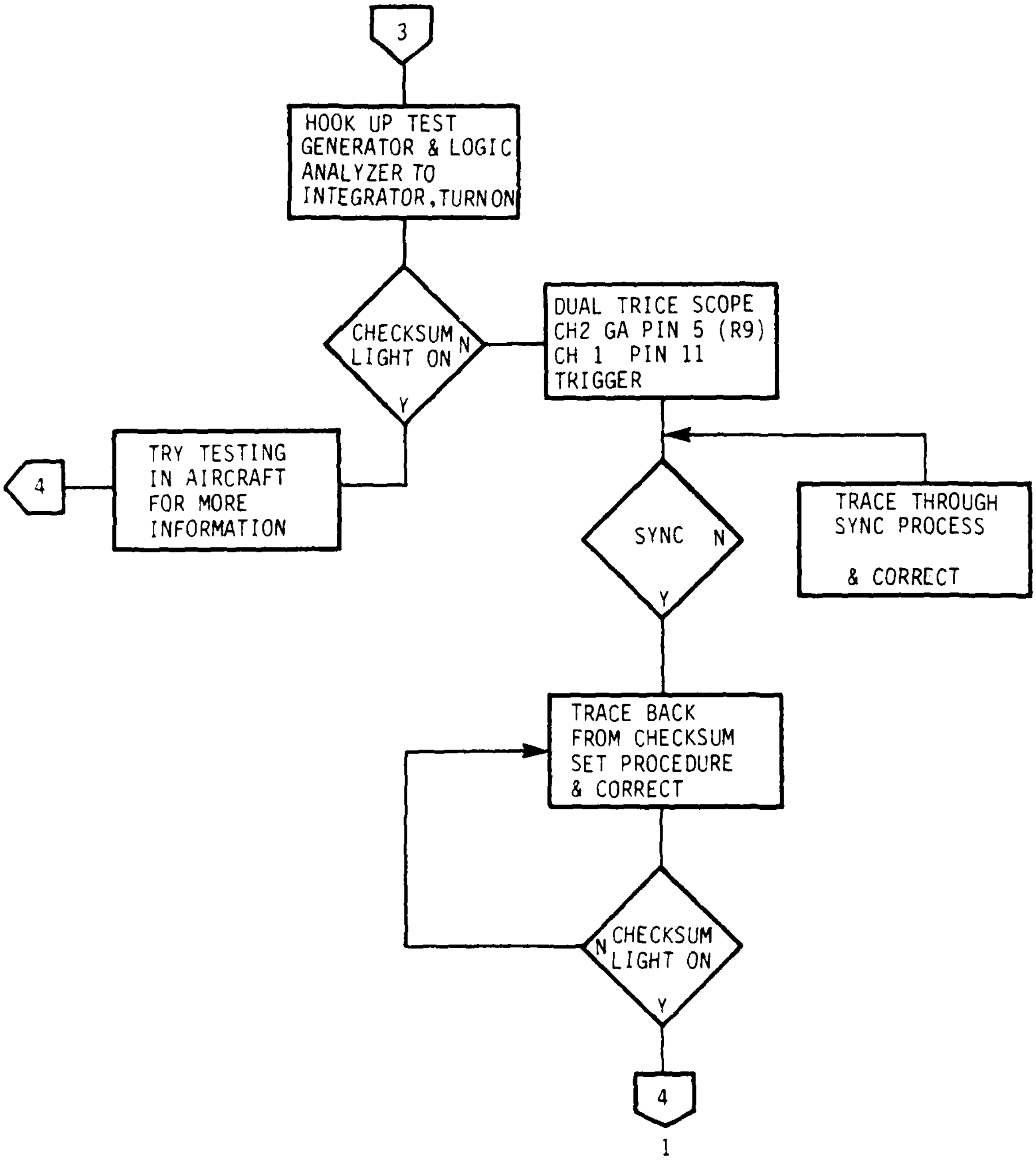


FIGURE 10. DIFFERENTIAL OMEGA TROUBLESHOOTING FLOWCHART.


1
7620 STATUS OK IN SKY
N
Y
CHECK ANTENNA, 7620 SOFTWARE, TRANSMITTED SIGNALS & CORRECT
5
SWITCH TO DIF
NOTE L , FAIL INDICATORS, CHECKSUM, 3115 3104, 3113, 0277
7620 STATUS OK IN DIF
N
Y
SYNC CONF 3115 OK (200)
N
Y
BIT SYNC CONF 3113 OK (100)
N
Y
LOCKUP PROBLEM? (FREQ OFFSET JITTER)
WORD CONFUSION BETWEEN US & TRACOR.
NOTE L CHECKSUM, ACTUAL POSITION FROM DME
NOTE WHAT STATIONS ARE MOOD R. (3202) TO SELECTED (0277)
CONTINUE TEST
7620 STATUS OK
Y
N
PROPER STATIONS SELECTED
N
Y
MANUAL SELECTION, RE-INITIALIZE?
OUT OF RANGE
N
Y
INSERT OLD PROM SET INTO TRACOR
END TEST
6
1


3
HOOK UP TEST GENERATOR & LOGIC ANALYZER TO INTEGRATOR, TURN ON
CHECKSUM LIGHT ON
N
Y
DUAL TRICE SCOPE CH2 GA PIN 5 (R9) CH 1 PIN 11 TRIGGER
TRY TESTING IN AIRCRAFT FOR MORE INFORMATION
4
SYNC
N
Y
TRACE THROUGH SYNC PROCESS & CORRECT
TRACE BACK FROM CHECKSUM SET PROCEDURE & CORRECT
CHECKSUM LIGHT ON
N
Y
4
1

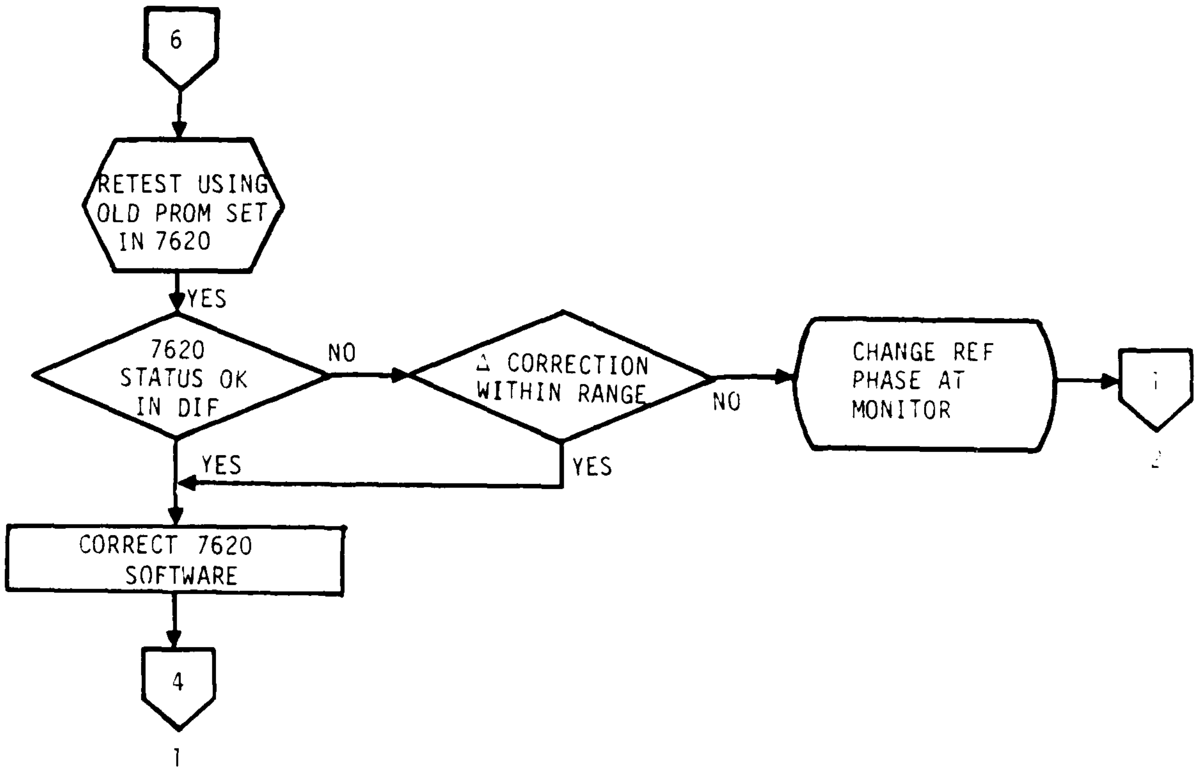

6
RETEST USING OLD PROM SET IN 7620
YES
7620 STATUS OK IN DIF
NO
Δ CORRECTION WITHIN RANGE
NO
CHANGE REF PHASE AT MONITOR
YES
YES
CORRECT 7620 SOFTWARE
4
1

Table 6

System Integrator Differential Message Format

WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
0	0 1 0 1 0 1 0 1	HEADER	N/A
1	0 1 0 1 0 1 0 1	HEADER	N/A
2	0 0 1 1 0 0 1 1	HEADER	N/A
3	[LOP1] [LOP2]	AREA PRIMARY LOP's	A 000 E 100
4	[LOP1] [LOP2]	AREA ALTERNATE LOP's 1	B 001 F 101
5	[LOP1] [LOP2]	AREA ALTERNATE LOP's 2	C 010 G 110
6	[LOP1] [LOP2]	AREA ALTERNATE LOP's 3	D 011 H 111
7	[LOP1] [LOP2]	AREA ALTERNATE LOP's 4	
8		CHECK SUM 3-7	N/A
9		AREA LOP1 C1 MSB	
10		AREA LOP1 C1	LANES x 2^{-12}
11		AREA LOP1 C1 LSB	
12		AREA LOP2 C2 MSB	
13		AREA LOP2 C2	
14		CHECK SUM 9-13	N/A LANES x 2^{-12}
15		AREA LOP 2 C2 LSB	
16		AREA LAT C3 MSB	
17		AREA LAT C3	SEMICIRCLES
18		AREA LAT C3 LSB	
19		AREA LAT C4 MSB	
20		CHECK SUM 15-19	N/A SEMICIRCLES/LANE 2^{-5}
21		AREA LAT C4 LSB	

Table 6
(Continued)

WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
22		AREA LAT C5 MSA	SEMICIRCLES/LANE 2^{-5}
23		AREA LAT C5 LSB	
24		AREA LAT C6 MSB	SEMICIRCLES/LANE 2^{-14}
25		AREA LAT C6 LSB	
26		CHECK SUM 21-25	N/A
27		AREA LAT C7 MSB	SEMICIRCLES/LANE 2^{-14}
28		AREA LAT C7 LSB	
29		AREA LAT C8 MSB	SEMICIRCLES/LANE^2 2^{-14}
30		AREA LAT C8 LSB	
31		AREA LONG C9 MSB	SEMICIRCLES
32		CHECK SUM 27-31	N/A
33		AREA LONG C9	
34		AREA LONG C9 LSB	
35		AREA LONG C10 MSB	SEMICIRCLES/LANE 2^{-5}
36		AREA LONG C10 LSB	
37		AREA LONG C11 MSB	SEMICIRCLES/LANE 2^{-5}
38		CHECK SUM 33-37	N/A
39		AREA LONG C11 LSB	
40		AREA LONG C12 MSB	SEMICIRCLES/LANE^2 2^{-14}
41		AREA LONG C12 LSB	
42		AREA LONG C13 MSB	SEMICIRCLES/LANE^2 2^{-14}
43		AREA LONG C13 LSB	

Table 6
(Continued)

WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
44		CHECK SUM 39-43	N/A
45		AREA LONG C14 MSB	SEMICIRCLES/LANE^2 2^{-14}
46		AREA LONG C14 LSB	
47	A B C D E F G H	10.2 kHz USABLE	
48	A B C D E F G H	13.6 kHz USABLE	
49	A B C D E F G H	11.1-1/3 kHz USABLE	"1" IS STATION USABLE
50		CHECK SUM	N/A
51	A B C D E F G H	11.05 kHz USABLE	
52		SPARE	
53		SPARE	
54		SPARE	SPARE
55		SPARE	
56		CHECK SUM	N/A
57	[MSB STATION A |		
58	|LSB] [MSB STATION B |		
59	| LSB] [MSB |	10.2 kHz PHASI CORRECTIONS	
60	|STATION C LSB] [MSB |		
61	|STATION D LSB] |		
62		CHECK SUM	
63	[MSB STATION E |		
64	|LSB] [MSB STATION F |		
65	| LSB] [MSB |	10.2 kHz PHASE CORRECTIONS	
66	|STATION G LSB] [MSB |		
67	|STATION H LSB] |		

Table 6

(Continued)

WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
68		CHECK SUM	N/A
69	[MSB STATION A	13.6 kHz PHASE CORRECTIONS	
70	LSB] [MSB STATION B		
71	LSB] [MSB		
72	STATION C LSB] [MSB		
73	STATION D LSB]		
74		CHECK SUM	N/A
75	[MSB STATION E	13.6 kHz PHASE CORRECTIONS	LANES x 10^2 x 2^{-8}
76	LSB] [MSB STATION F		
77	LSB] [MSB		
78	STATION G LSB] [MSB		
79	STATION H LSB]		
80		CHECK SUM 81-85	
81	[MSB STATION A	11.1-1/3 kHz PHASE CORRECTIONS	
82	LSB] [MSB STATION B		
83	LSB] [MSB		
84	STATION C LSB] [MSB		
85	STATION D LSB]		
86		CHECK SUM 81-85	
87	MSB STATION E	11.1-1/3 kHz PHASE CORRECTIONS	
88	LSB] [MSB STATION F		
89	LSB] [MSB		

Table 6
(Continued)

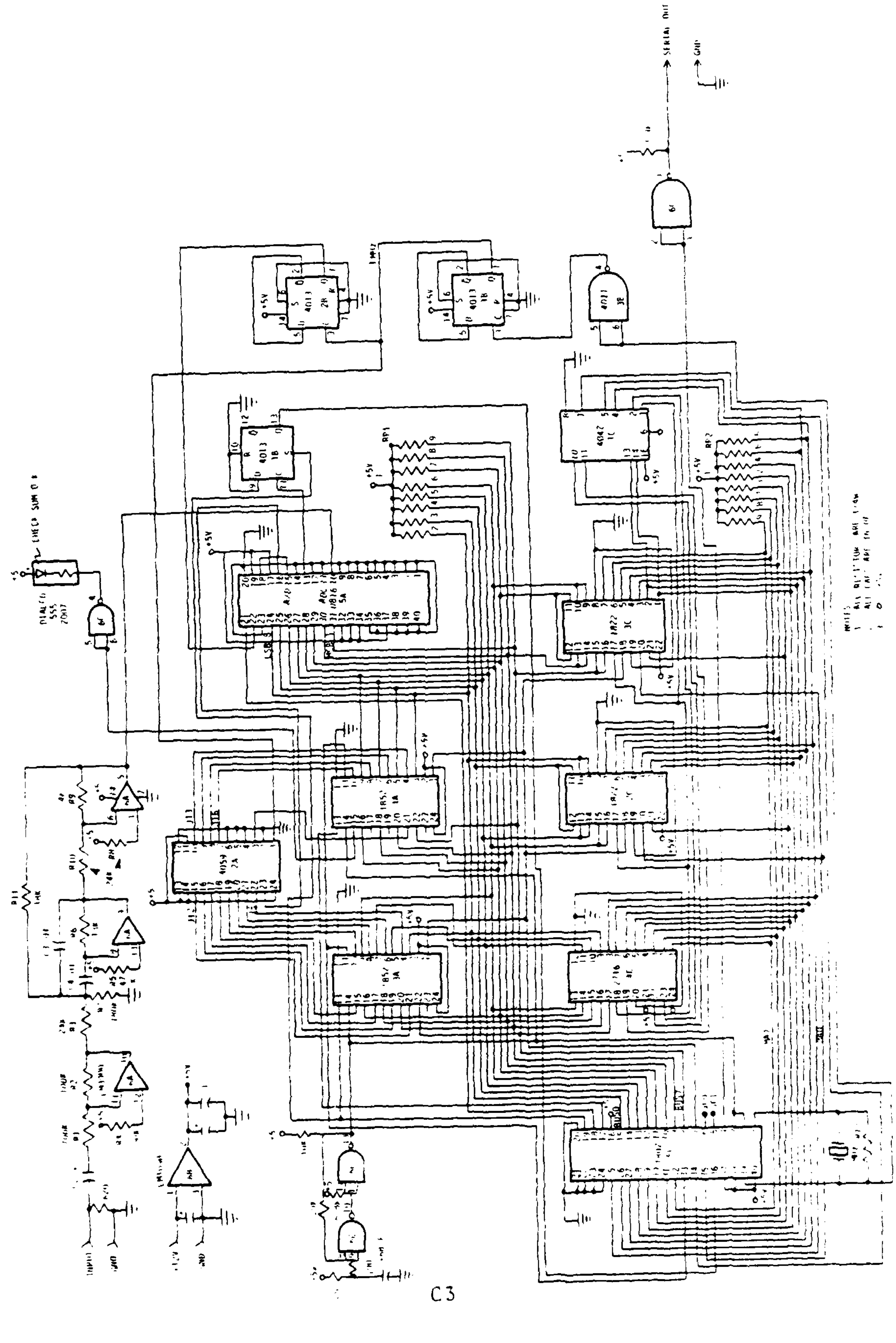
WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
90	| STATION G LSB] [MSB |		
91	| STATION H LSB]		
92		CHECK SUM 87-91	
93	[MSB STATION A |	11.05 kHz PHASE CORRECTIONS	
94	| LSB] [MSB STATION B |		
95	| LSB] [MSB |		
96	| STATION C LSB] [MSB |		
97	| STATION D LSB]		
98		CHECK SUM 93-97	
99	[MSB STATION A |	11.05 kHz PHASE CORRECTIONS	
100	| LSB] [MSB STATION B |	11.05 kHz PHASE CORRECTIONS	
101	| LSB] [MSB |		
102	| STATION C LSB] [MSB |		
103	| STATION D LSB]		
104		CHECK SUM 99-103	N/A
105	[MSB STATION E |	11.05 kHz PHASE CORRECTIONS	LANES x 10^2 x 2^{-8}
106	| LSB] [MSB STATION F |		
107	| LSB] [MSB |		
108	| STATION G LSB] [MSB |		
109	| STATION H LSB]		
110		CHECK SUM 105-109	N/A

Table 6
(Continued)

WORD	BITS 0 1 2 3 4 5 6 7	DESCRIPTION	SCALING
111			
112			
113			
114			
115			
116			
117		SPARE	
118			
119			
120			
121			
122			
123			
124			

APPENDIX C

LOGIC DIAGRAM SYSTEM INTEGRATOR BOARD



APPENDIX D

FINAL TECHNICAL REPORT

DIFFERENTIAL E-FIELD NOISE-CANCELLING ANTENNA SYSTEM

1.0 SUMMARY

Limited flight testing of the Differential E-Field Antenna System, designed to provide cancellation of precipitation-static interference in airborne Omega applications, has been undertaken with the experimental equipment installed in the FAA Convair 580 aircraft (tail number N90) at the FAA facility, Anchorage, Alaska. Test results from brief periods of operation on two available flights were basically inconclusive, although some reduction in precipitation-static interference was qualitatively observed.

The first part of this report describes some observations and conclusions from the preliminary flight testing. A description of the experimental system is given in the subsequent section.

2.0 FLIGHT TEST RESULTS

Operation of the noise-cancelling, differential E-field antenna system was limited, due to higher priority of the primary Differential Omega task program, to brief intervals during two flights on October 17 and 19, 1980. The basic problem on each of these flights was poor signal reception on the lower antenna (refer to Fig. 1 and Section 3 for a description of the system configuration). Clean, strong Omega signals were normally receivable from the upper E-field antenna (mounted atop the fuselage at station location 550). However, measurement of relative Omega signal strength (using strong Hawaii Omega as the reference) showed that the signal from the lower antenna/preamplifier was some 10 dB weaker than the same signal from the upper antenna/preamplifier unit. In addition, the lower antenna/preamplifier indicated a 3-4 dB higher noise level (implying an overall degradation in signal/noise ratio of perhaps 13-14 dB for the lower antenna). These measurements were made by observations of the relative signal level and noise level meter readings with the Omega Noise Analyzer (ONA).

The poor signal/noise reception characteristics of the lower antenna unit could also be confirmed by earphone monitoring of Omega signal quality. All three on-the-air Omega stations (Norway, Hawaii and N. Dakota) were clearly audible (at least during non-precipitation static conditions) from the upper antenna; however, only Norway or Hawaii was audible with the lower antenna.

This gross inequality in signal reception between upper and lower antenna units made it impossible to obtain a good noise-cancelling null. (Cancellation by the differential antenna concept requires nearly complete correlation in noise components receivable at the separate upper and lower antenna

AD-A107 857 SYSTEMS CONTROL INC (VT) PALO ALTO CA F/G 17/7
DIFFERENTIAL OMEGA SYSTEM DEVELOPMENT AND EVALUATION.(U)
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antenna locations. Uncorrelated noise, if present, simply cannot be nulled).

Several steps were taken in an attempt to isolate the source of this interference. The individual preamplifiers associated with the upper and lower E-field plate antennas operate on regulated $\pm$ 12 volt d.c. power derived, via shielded cabling, from a single laboratory-grade a.c. power supply within the ONA equipment cabinet. Switching of this power supply from the normal 400 Hz aircraft power source to a 60 Hz power source (i.e., by use of the separate 60 Hz inverter located in the rear of the FAA aircraft) produced no noticeable change in signal/noise level. Similarly, it appeared to make little difference whether or not the ONA instrumentation cabinet was directly grounded to the airframe.

The upper and lower preamplifier units were also exchanged, between the first and second flights, on the possibility that the poor signal reception was somehow associated with the lower preamplifier. However, excessive noise was again observed from the lower antenna on the next flight.

It may therefore be concluded that the observed poor signal reception from the underneath antenna was due either to a high ambient noise field surrounding the lower antenna or, less likely, to some interference picked up via the interconnecting cable between the lower preamplifier unit and the ONA instrumentation cabinet. There was no opportunity to re-route this cable or to determine whether significant noise was indeed being coupled into the interconnecting cable.

(It should be noted that any problem associated with the lower antenna is complicated by the fact that Omega signals cannot be normally received by an underneath-the-fuselage

E-field antenna while the aircraft is on the ground. The conductive airframes virtually shorts out the electric field in the narrow region between the fuselage and the earth. Of course, once the aircraft is airborne, this shielding effect disappears and normal signal reception from an underneath-the-fuselage antenna is possible).

Another simple test suggests that the lower antenna was located in a region of high ambient noise. A marked reduction in the receiver output noise level was observed when the lower antenna was shielded from the surrounding electric field. This shielding was effected by totally enclosing the E-field plate antenna (at a spacing of 3 - 4 inches) with aluminum foil which was then grounded to the aircraft fuselage skin. This test was made during a delay prior to the scheduled take-off time so that only a qualitative measurement (via earphone monitoring of the noise reduction produced by electrical shielding of the antenna) was taken. Moreover, it should be noted that this type of test (with aircraft on ground and with landing gear doors opened so as to expose the lower antenna to other possible interference sources) may not be indicative of the actual noise level during flight (with the closed doors then providing some additional electrical shielding).

The signal balancing unit and the noise analyzer/receiver operated satisfactorily on both flights. A null balance approaching -23 dB was obtainable on the internal BITE test signal (e.g., switching from the additive A + B antenna mode to the noise-cancelling, differential A - B mode required a 23 dB increase in receiver gain to produce an equivalent meter output signal). Furthermore, switching OFF the BITE signal under this condition produced no further reduction in meter output reading for the A-B mode (indicating that the -23 dB "null" reading was limited by non-coherent noise rather than by an imperfect adjustment of the phase/gain balance controls for the BITE signal itself).

By operating in the A + B mode it is also possible to obtain a null balance on the incoming Omega signals. The level of the received Omega signals is considerably weaker than that of the BITE test signal; accordingly, the quality of the realizable null on any Omega station signal, in the presence of the extraneous noise from the lower antenna, was limited to roughly -14 dB (in switching from the normal A - B mode to the A + B mode of operation).

It should be noted that optimal adjustment of the gain and phase balance controls so as to achieve desired cancellation of p-static interference (in the A - B differential antenna mode) need not coincide with the comparable adjustment for nulling of the BITE signal (also in the A - B differential mode) or for Omega signal nulling (in the A + B antenna mode). Initial nulling on BITE signals, however, does provide a simple, convenient means of coarse adjustment of the gain/phase controls that can be used by the operator prior to observing any p-static interference. Once variable p-static is encountered, unless a moderately good coarse null has already been achieved, it is exceedingly difficult to determine even the proper direction of an adjustment to either the phase or gain controls.

On the first flight, aircraft power to the instrumentation was temporarily switched off immediately prior to take-off. Precipitation static was then encountered during climb-out through overcast clouds in the Anchorage area. Such operational problems, coupled with the excess noise from the lower antenna, prevented the collection of more meaningful test data on either flight.

The susceptibility of single E-field antennas to precipitation-static interference was clearly demonstrated on both flights. Moderate-to-severe p-static was observed at various times. The most severe interference appeared during periods of aircraft turbulence. Under these conditions the normally strong Omega signals (Norway, Hawaii, N. Dakota) from the upper antenna would be totally obliterated by noise having a surging characteristic (as evidenced in earphone monitoring).

Under less severe interference conditions, one or more of the Omega signals would be barely audible on the upper antenna (identified as the A mode of operation) and totally inaudible on the lower antenna (B mode). There were several occasions that the corresponding Omega signal from the differential antenna mode of operation (in the A - B mode) would show a cleaner signal characteristic than that obtainable from either antenna alone. From these qualitative observations it might be concluded that the differential antenna system was indeed providing some small measure of p-static noise cancellation.

Attempts were then made to improve the differential A - B signal by adjustment of either the gain or phase balance controls. The variability in the noise interference level, however, obscured any changes in signal quality that may have been produced by this trial-and-error adjustment procedure.

Several conclusions and recommendations can be drawn from this limited flight testing:

1) Clean Omega signal reception was obtainable from the upper plate antenna (under p-static free conditions). This demonstrated that the plate antenna/preamplifier combination has adequate sensitivity.

2) The lower antenna, however, introduced an excessive level of electrical noise, both on the ground and during flight. Uncorrelated noise of this type must be eliminated if successful p-static cancellation is to be realized.

3) There is no immediate explanation for the large noise level associated with the underneath antenna. Preliminary tests suggest, however, that the noise is entering through the antenna directly (i.e., that the antenna is located in an unusually high noise field). If thise noise field is sufficiently localized, it should be possible to eliminate, or materially reduce, the interference by a re-location of the lower antenna (say, by moving the antenna aft by 5 feet or more).

4) Oscilloscope monitoring of each preamplifier outputs should be employed to determine whether any saturation or limiting action is occuring during impulsive p-static conditions. (The antenna/preamplifier combination used in this flight testing operated satisfactorily up to an electric field strength level approaching $\pm$ 5 volts/meter; however, oscilloscope monitoring of output waveforms would have been useful in confirming that these levels were not excluded during the most severe p-static interference).

5) Additional flight time should be scheduled to provide operator experience and to verify that all portions of the system are operating satisfactorily prior to data collection.

3.0 SYSTEM DESCRIPTION

A brief description of each of the functional components of the aircraft instrumentation is as follows:

3.1 E-Field Antennas

A pair of low silhouettd, capacitive-plate antennas, one mounted atop the fuselage and the other beneath the aircraft (both located near station 550 on the convair 580 aircraft), are used for Omega signal reception. Thge antenna housing is an electrically insulated fiberglass shell with a conductive coating painted over the central region (with this conductive region forming a capacitive plate antenna with respect to the aircraft skin). A relatively small antenna of this type, with an effective height-capacitance value in the neighborhood of only 2×10^{-13} farad-meter, requires an extremely good preamplifier if input circuit noise is to be avoided. However, a physically small antenna, particularly in the height dimension, reduces the risk of particle impingement that can, in itself, be a source of p-static interference. A flush mounted antenna would be even better, but this would pose an additional installation problem for the FAA Convair 580 and other aircraft.

3.2 Antenna Coupler Preamplifier)

An active coupler/preamplifier is used with each antenna. Each preamplifier, mounted inside the aircraft, is connected to its antenna via a 9" coaxial cable. Transformer coupling of the antenna input circuit is used to provide isola-lation to any power or common mode input noise. An electric-field strength sensitivity in the neighborhood of 1 volt/meter - $\sqrt{Hz}$ at the 13.6 kHz operating frequency was measured in the laboratory (preamplifier used in combination with the above E-field plate antenna).

3.3 Signal Balancing Unit

The Signal Balancing unit includes both phase and amplitude balance controls so that the common mode component of the p-static noise can be nulled out; in addition, the unit includes a reversing switch (in the B channel). The reversing switch is useful in initial coarse null balancing and in measuring the quality of the null during p-static conditions.

The A-B position should show a deep null on p-static if the phase and amplitude controls are properly balanced for p-static suppression. Conversely, in the A + B position, the received Omega signals and atmospheric noise will tend to be nulled out, leaving p-static and other common-mode noise as the major component.

3.4 Omega Noise Analyzer

Each Omega Noise Analyzer (ONA) includes both a wide band filter output capability (approximately 200 Hz bandwidth) and a narrow band output (less than 1 Hz). The wide bandwidth is most useful for the measurement of noise; the narrow band filter, centered at 13.6 kHz, permits a direct measurement of Omega signal strength.

The operator can select, by means of a thumbwheel switch, a particular Omega segment to be used for time gating of the wide band filter; similarly, a second Omega segment can be selected for the narrow band filter outputs. The time-gated waveforms are rectified and averaged over the selected segment interval. A sample-and-hold circuit displays the resultant average value on front-panel meters: once every 10 seconds the front-panel meters display new signal (or noise) coverages. Each ONA channel has independent gain/attenuator controls so that useful, on-scale meter deflections can be obtained over a wide range of input signal (or noise) levels.

In addition to the front-panel meters, each ONA channel includes provision for earphone monitoring and magnetic tape recording (of the ungated 200 Hz bandwidth signals + noise).

Heterodyne conversion of the 13.6 kHz Omega signals to a 1024 Hz intermediate frequency (i.f.) is employed. Phase and amplitude information is retained in this process.

3.5 Tape Recorder

It had been originally planned that a Hewlett-Packard 3964A Instrumentation Recorder be procured and used for 4-channel recording of the following ONA output channels:

Channel 1: Single Antenna A

Channel 2: Differential Antenna A - B
(or A + B through switch reversal)

Channel 3: Single Antenna B

Channel 4: Loop Antenna

Channel 1 and 2: Data logging is obtained from one

ONA unit; Channel 3 and 4 recording would have been possible from a second ONA unit (with the fourth channel designed to give information on the comparative behavior of loop vs differential E-field antenna under identical p-static conditions).

However, time and funding restrictions prevented procurement of the 4-channel instrumentation for this particular flight test series. Instead, a readily available 2-channel cassette recorder (similar to an ordinary portable cassette recorder, but with dual channels for stereo recording purposes) was incorporated into the instrumentation package. The recorder was then modified to provide more linear performance over its full dynamic range by removal of its automatic level recording circuit. Laboratory testing showed that the resultant recorder had an adequate analog data recording capability, with correct phase and amplitude data being displayed in playback of the dual channels.